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COAL DUST

AN

EXPLOSIVE AGENT

WITH SEVEN PLATES

DONALD M. D. STUART, F.G.S.

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COAL DUST
AN
EXPLOSIVE AGENT:
AS SHOWN BY AN EXAMINATION OF
THE CAMERTON EXPLOSION.

With Seven Plates.

BY
DONALD M. D. STUART, F.G.S.,
MINING AND CIVIL ENGINEER.

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P R E F A C E.

THE operations of mining and the production of coal are conducted in circumstances that command public sympathy. Their history contains many sad pages of disaster, and the explosions to which they are subject, have caused an appalling loss of life. These calamities have appeared to be inexplicable. Royal Commissions have been appointed to investigate them; and the numerous mining institutions of the country, have long records of voluntary labour and expenditure in elucidating the dangers, and discovering the remedies. The origin and conditions of a fire-damp explosion are now well known and provided against; but explosions still occur, and a mine that is supplied with all the arrangements and precautions that experience and science can suggest, is suddenly transformed into a chamber of death. It has been evident for some time, that a danger other than fire-damp lurked within the mine, and its discovery has been laboriously sought by inspectors of mines and mining engineers. This contributory danger was suggested to be coal-dust, and the last Royal Commission upon Accidents in Mines investigated the subject; the results, however, were not conclusive, and a Royal Commission is now engaged in attempting its elucidation.

The subject is complicated by a wide diversity of experience and phenomena, and in the nature of the case the part which coal-dust may take in an explosion in a mine, cannot be a matter of observation, as it is fatal to the observers. The danger is difficult to elucidate, even under

the highly-organised scientific and practical management and inspection to which all mines are now subjected. Scientific and experimental researches have been conducted, and the results applied to the examination of explosions in recent years, which permitted only the conclusion that coal-dust was a contributory danger in a gaseous mine, and would propagate explosions of gaseous mixtures. The chemical and physical activities produced by the presence of coal-dust, however, remained a matter of speculation, as the phenomena were complicated by the action of fire-damp, and it was difficult to allocate to each agent its individual functions. Fire-damp was an acknowledged danger ; but a large experience had failed to establish such a character for coal-dust, and the non-gaseous mines possessing a historical freedom from explosions, no opportunity had arisen to investigate the phenomena of an explosion in which coal-dust was the exclusive agent.

In November last an explosion occurred at the Camerton Collieries, Somersetshire, a non-gaseous mine, which afforded the occasion for studying the features of an explosion produced by an agent other than fire-damp, and of elucidating a hidden danger in coal-mining. I was consulted by Mr. T. Y. Garthwaite, the general manager of the collieries upon the matter, and was engaged for five days in the mine, during the months from January to April last, investigating the phenomena of the explosion. The drawings which embodied the data of my investigations were submitted to the Royal Commission inquiring into the coal-dust question, by Mr. Garthwaite in his evidence upon the explosion. It subsequently appeared to me that, this being the first explosion in a non-gaseous mine, it called for a special study of the subject, and Mr. Garthwaite coinciding with my idea, I have prepared this work.

The object I have sought is to present a description of the phenomena of the explosion ; to locate its origin and trace its propaga-

tion ; to inquire into the source and character of the gaseous mixtures to which the initial gaseous explosion, and the subsequent propagations were due ; the nature and sufficiency of the physical and chemical activities for the effects produced ; and to indicate the conditions under which the explosion was commenced, propagated, and stopped. The great importance of the subject of coal-dust as a hidden danger in coal-mining, and the public attention it commands, must be my justification for the careful study of detail which this book records. It appeared to me to be necessary to record all that I had observed, and the information given to me by Mr. Garthwaite and his under-manager, Mr. J. Moon, to establish substantial grounds for the conclusions I have ventured to offer ; and to give other investigators the fullest assistance in their study of the circumstances of this grave danger, so that uncertainty and doubt may be removed, and the presence and nature of a real peril demonstrated.

I have pleasure in thanking Mr. Garthwaite for the plan and section of the colliery, from which Plates I. and II. have been prepared, and for the information and assistance he gave me in my investigations of the explosion ; also in thanking Mr. J. Moon for his assistance in my inspections.

DONALD M. D. STUART.

Bristol, June 9th, 1894.

INTRODUCTION.

A N explosion is the most dreaded accident in a mine. It occurs unexpectedly, without warning, and its destructiveness and magnitude baffle both conception and control. An explosion of gas in a house means the destruction of a room, or partial damage to the building, and the dissipation of surplus energy in the atmosphere. In a mine the gas is confined in a labyrinth of tunnels, where its potentiality is conserved, and is wholly expended in destroying life and wrecking the roads and ventilating arrangements. The ventilation being suspended, the air of the mine is changed into a stagnant and poisonous atmosphere insidiously fatal to any life that has escaped the mechanical violence of the explosion. The records of mining show that explosions cause greater destruction of life and property than any other class of accident.

The subject of explosions has received the constant attention of mining engineers and colliery managers, and an immense amount of thought and labour has been given to elucidate their origin and the conditions of the activities and violence they exhibit. New methods of working mines have been developed, ventilation has been largely increased, and improved safety-lamps adopted, with the result that these disasters have been diminished in the frequency of their occurrence.

Until comparatively recent years it was the generally-received opinion of the mining world, that explosions were due to the explosive ignition of a hydrocarbon gas termed methane, popularly called fire-damp.

The panacea appeared to be in the provision of effective safety-lamps, and of an adequate amount of ventilation to dilute this gas, and thus make it innocuous. Closer investigation of the phenomena of explosions, and their apparently mysterious developments, has, however, revealed a contributory cause. They have been traced, and found to traverse roads and to effect mechanical violence where gas could not be conceivably present, and at points remote from the origin of the disturbance. Coal-dust in a coked and cindered condition was observed secreted on the timber, showing that it had been subjected to intense heat and had yielded up its hydrocarbon gases. Upon these evidences the suggestion arose that the coal-dust, when exposed to the heat generated in the explosive ignition of fire-damp, became a contributory source of gas, and propagated the explosion into districts that otherwise would have remained unaffected.

Experimental investigations were conducted with the object of discovering the functions of coal-dust in such circumstances by Mr. W. Galloway, Mr. H. Hall, the late Professor Freire Marrecco, Mr. D. P. Morrison, Mr. Lindsay Wood, Mr. G. May, and the Chesterfield and Derbyshire Institute of Mining Engineers, and the results showed that a fire-damp explosion was propagated by coal-dust. Mr. W. Galloway proved that if air containing a small percentage of fire-damp were saturated with coal-dust it became inflammable. So far an explosion was attributable to two causes—(a) a mixture of fire-damp and air in explosive proportions ; (b) a mixture of fire-damp and air in inexplosive proportions, but holding coal-dust in suspension.

These conclusions were generally accepted, and there was no reasonable doubt that coal-dust had been an important factor in the development of several explosions of fire-damp.

The subject was carried further by Mr. H. Hall and Mr. W.

Galloway, who suggested that coal-dust itself would produce the phenomena of an explosion ; and, in a number of experiments extending over several years, Mr. H. Hall effected many ignitions of dust-laden air, with violence, when the air was presumably free from fire-damp. These experiments were conducted under conditions that did not obtain in a mine, and the results were inconsistent with a large amount of practical experience. The dust in mines had been known to ignite and burn, on many occasions, without causing anything in the nature of an explosion ; and there was a widespread scepticism that it could, in the absence of an explosive accumulation of fire-damp, produce an explosion in a gaseous mine ; and the dust of non-gaseous mines was believed to be innocuous.

The investigations were continued with great ability at home and on the Continent ; past explosions were reconsidered with the evidences yielded in these scientific and practical researches ; and ultimately the coal-dust theory was propounded. It was incumbent upon the advocates of that theory to explain the origin of a source of heat, other than that due to the explosive ignition of fire-damp, adequate to distil gases from the coal-dust ; the nature of the explosive gaseous mixture so produced, and the physical and chemical activities involved in the propagation of explosive phenomena. Their views are given in evidence before the Royal Commission now sitting upon the subject, and published in the First Report.

The case is stated by Sir Godfrey Lushington, C.B., and the scientific and practical features are given by Sir Frederick Abel, K.C.B., and Messrs. H. Hall, W. Galloway, J. B. Atkinson, and W. N. Atkinson. It is stated that where fire-damp is absent, an explosion can be produced from coal-dust by the products of the ignition of an explosive like gunpowder, and by "Other causes" which are not given ; but that "Flame

must be the agent to start it.”* The dust is required to be fine and dry, the descriptive terms being “Fine as fluff,” “Porous,” “Impalpable,” and the accumulations on the timber and the “Higher parts” of the roadways” above the floor are defined as dangerous.† This dust, it is said, must not be in a “State of rest,” but raised by the initial explosion, to form “A cloud of dust in the air thick enough to enable it to carry flame,”‡ termed the “Pioneering cloud.”

The propagation of the explosion is described as follows:—“The theory, I believe, is this: that, by some means or other, a cloud of dust is disturbed, is ignited, and explodes. The explosion of that first cloud starts another, ignites it, and explodes it; the second does the same to the third, and the third does the same to the fourth, and so on through the pit, so long as there is a dust supply.” “They succeed each other so quickly as to be almost simultaneous.” “There are certainly not a number of independent explosions.”§ The “Pioneering cloud” of dust, it is said, is followed by the “Flame,” which “Fills the air road,” like a “Diaphragm of flame, as it were, travelling along the road,” and is compared to “A rush of flame along the roads from the commencement to the finish;” and, it is added, “The combustion in that diaphragm would be gradually getting more fierce, or exerting greater force.”||

The foregoing idea of propagation is illustrated by a figure of a “Very long cannon,” which is loaded and fired; and the development of a coal-dust explosion is compared with the action that occurs as the fired charge travels along the bore. The question asked was: that assuming an explosion was set up in the end of a gallery 50 yards long, “Whether the explosion was intensified and continued, or repeated—whether new explo-

First Report of the Royal Commission on Explosions from Coal-dust in Mines:—

* Questions 82, 83, 84, 233, 2,174, 2,176, 2,177.

† Questions 1,032, 2,129, 2,230.

‡ Questions 350, 528, 529, 661, 1,199, 2,205.

§ Questions 9, 10, 11, 2,129, 2,130.

|| Questions 1,032, 509, 704, 2,130.

sions were set up in the course of the length of the gallery?" The reply was:—"I should say, in reply to that question, that the illustration which you have taken as regards cannon and powder affords a very good kind of illustration of the effect of coal-dust in carrying on explosions. In ordinary parlance there would be only one explosion in firing a gun, but in point of fact the explosion is continued, and, especially in powders of modern nature, is taken up by successive portions of powder as the products of the first explosion pass along the gun, so that the explosion is prolonged or continued, or, if you like to sub-divide it, consists of a series of explosions proceeding along the whole bore of the gun. And in the same way I consider that the flame of a first explosion meeting a mixture, which in itself is more or less explosive, of coal-dust and air, as it passes along is transmitted, and the explosion in that sense is continuous, as it would be in the gun, so long as there is a sufficient quantity of explosive mixture to develop heat enough and products enough to carry the explosion further."*

The evidences of the travel of the "Pioneering cloud" of dust and the "Flame," are given as the deposits of coked coal-dust on the timber of the roads, which indicate that the dust had been exposed to a high temperature. This coked dust is observed to be "Generally deposited on the sides opposite the direction in which the explosion has travelled." "We will suppose the explosion is travelling in this direction (illustrating). Assuming this to be a prop in the mine, you would imagine the coked dust would be thrown on that side; instead of that, it is usually found on this side." "It seems to be thrown on to the timber by a backlash."†

It is suggested that the explosion displaces the air current to permit

First Report of the Royal Commission on Explosions from Coal-dust in Mines:—

* Question 2,394.

† Questions 706, 707, 2,361.

the flame to travel ; that the air is “ Bodily moved along the road,” “ In front of the explosion,” “ Beaten back ;” and when “ The force of the explosion is very great, it still has a large body of air to displace before it can extend the flame.”*

It is observed that the “ Flame ” often travels against the air current, and takes “ Apparently a choice of routes,” traversing one road and avoiding another equally accessible. The explanation offered is that the dusty roads are traversed, and the non-dusty ones omitted.†

The conditions necessary to arrest the progress of the “ Flame ” are supposed to be dust-free, or wet, spaces of road. As regards dust-free spaces, it is suggested that the flame would jump over 50 to 100 yards of road in that condition. In wet spaces, the flame is said to have jumped over 67 yards of road at Usworth, where the floor was damp, but the sides dry and dusty. The opinion was expressed that 50 to 100 yards of wet road would not arrest the flame after the explosion was once set going ; but a case was referred to where 200 yards of wet floor had done so.‡

Other suggestions have been made of circumstances in which the flame may die out—one by Mr. James Lucas, who himself observed an explosion which he describes as produced from coal-dust, and states that it “ Exhausted itself ” where it obtained sufficient room to expand.§ Mr. W. E. Garforth suggests that “ Dirt dust ” may be the means of preventing the propagation of the explosion on some roads.|| It should be remarked here that the important and valuable matter and drawings of the Altofts explosion, prepared by Mr. W. E. Garforth, and given by him to the Royal Commission, commanded a wider attention for the question than it had hitherto received.

First Report of the Royal Commission on Explosions from Coal-dust in Mines :—

* Questions 507, 803.

+ Questions 2,197, 2,198, 2,135.

‡ Questions 741, 742, 744, 745, 325, 1,169.

§ Questions 3,201, 3,209. || Question 3,774.

The development of the coal-dust theory in the foregoing conditions and features shows the assiduity and ability with which the subject has been investigated, and the minute observations made of the phenomena of explosions. Although the theory did not find general acceptance, some of the conditions being considered impracticable and difficult to understand, its advocates advanced a case for consideration which challenged inquiry and discussion, and effected the public recognition of the subject by the appointment of a Royal Commission for its examination. The Royal Commission has taken evidence on the subject broadly, and the conclusions are awaited with considerable interest.

The difficulties in the coal-dust theory were the absence of any adequate explanations of the initiation and the propagation of an explosion. It was not easy to conceive that the products of a charge of gunpowder, of the dimensions that usually obtain in coal-mining, could be adequate to set up and maintain distilling action in the coal-dust from the shot to the initial explosion, and retain residual heat to ignite the gaseous body produced. When the exploded gunpowder dislodges its burden, the products of the combustion escape over the area of rupture and are scattered; they reach the dust in that case, if at all in an attenuated condition in force and in temperature. If the gunpowder fail to break down its burden, then the products would escape with propulsive force and high temperature into the road; but it was difficult to understand how they could shake up the dust into intimate admixture with the air, carry on combustion in that mixture producing explosive violence, and withal leave a survival of heat to propagate explosive phenomena. Granting that the gunpowder products were capable of disengaging hydrocarbon gases from the coal-dust in admixture with air, and that by virtue of the flame present combustion proceeded in the atmosphere of gases thus produced, the phenomena of explosive violence and propaga-

tion of the explosion presented difficulties. It was observed that "In the actual explosions from the point of ignition for some 50 to 100 yards no great force was developed."* The exhibition of mechanical violence at that distance from the point of ignition, necessitated the presence there of an explosive gaseous mixture, and its explosive combustion; and propagation involved the generation of heat in these chemical activities adequate to recommence the gas-generating processes in the dust and repeat the phenomena. The suggested processes leading up to the initial explosion produced from coal-dust, no less than those offered to explain propagation by successive clouds of dust each set up on the explosive ignition in its predecessor, and exploded with its residual heat, did not appear to provide for the effects of the combustion said to be in progress in each cloud. The suggested rush of flame through hundreds and even thousands of yards of road apparently did not contemplate the quantity of heat it must have yielded up by contact with the cold air, and by impinging upon the immense extent of cooling surfaces presented by the enclosing walls of the road.

To illustrate propagation it was compared with the development of the explosion of gunpowder in a long cannon, where the processes of combustion develop along the bore. This development is due to the initial charge in the breech of the cannon. There is no accession of power, the bore being absolutely free from any additional explosive agent. The conditions required by the coal-dust theory were, that besides the explosive charge in the breech, there should be an additional agent in the form of coal-dust distributed along the bore, to form the cloud of dust, without which propagation was impossible. The illustration appeared to compare with a mining shot, in which the explosive agent had failed to rupture the walls of the hole, and its products were there-

fore expelled into the free atmosphere of the mine; and it was difficult to conceive how a continuous series of explosive combustions could proceed in the dust in the road, comparable with those developed in the bore of the cannon.

It was suggested that propagation proceeded by a rapidly-moving cloud of coal-dust carrying flame, and the conclusion was obvious that, if the heated particles of coal-dust were deposited anywhere, it would be upon the faces of the timber opposed to its travel. The contrary was the case; the particles of coked coal were found upon the opposite, or sheltered faces of the timber. How this moving cloud failed to deposit its suspended matter in its onward march, and yet, did so on its recoil (the suggested explanation) was inexplicable. Again, this moving cloud of coal-dust undergoing combustion, must have left evidences in its progress in deposits of solid matter upon the faces of the timber and strata brought about by its impingement upon them; but none are recorded. The processes and conditions advanced in the coal-dust theory were consequently involved in serious difficulties; and the possibility of an explosion being produced from coal-dust was inconsistent with a great weight of experience. The initiation and propagation of an explosion from that agent, therefore, remained in doubt.

Up to this time, all the explosions in mines had occurred where fire-damp was more or less present; and non-gaseous mines were historically free from such disasters. There was apparently some important difference between the coal-dust in gaseous and non-gaseous mines, as the former had undoubtedly something to answer for in many large explosions; but only the coal-dust of seams yielding fire-damp could be claimed for the coal-dust theory.

Experimental investigations were made by Professor Bedson to ascertain why coal-dusts vary in inflammability when mixed with air,

or brought into contact with a light ; and he discovered that they were distinct in character, that they yielded different volumes of gas and different gases under the conditions of experiment ; some yielded hydrocarbons of the paraffin and olefiant series, but others yielded none.*

These investigations appeared to offer a possible solution of the question of the freedom of non-gaseous mines from explosions. Many of these mines are in the South-Western district, they all contain more or less dust in a dry or damp condition, gunpowder has been largely used in them, and during a history of one hundred years there had been no explosion. Various incidents in the operations of these mines have led to the conclusion that the dust they contained was innocuous. In a colliery under the author's management, one of the seams worked was dry and warm, and the dust was fine and mobile. This dust heated in the goaf, and rapidly developed a fire. During a short stoppage, the fire reached an intake air-way, which at this point was thickly strewn with dust. When discovered, the floor for about 40 yards was covered with tongues of yellow flame rising off the dust, and running up the feet of the timber. The air-current was immediately diverted, and the flames died out. The conditions of fineness and dryness of coal-dust, and the presence of flame, required by the coal-dust theory, obtained here ; but there was no explosion, nor any mechanical violence. The author has also frequently observed that the air in the working faces of non-gaseous seams contained much fine coal-dust in suspension, and that the products of exploded gunpowder were projected into this air without producing any explosive phenomena, or the ignition of the dust.

In May and July of last year, Mr. H. Hall renewed his experiments with coal-dust in an old shaft, the air being free from fire-damp. The

dust to be tested was scattered into the shaft, and a cannon charged with $1\frac{1}{2}$ lb. of gunpowder, and lightly stemmed with an equal volume of coal-dust, was fired up the axis of the shaft into the dust-laden air. The results showed that some dusts from gaseous mines were explosive agents in the conditions that obtained in the experiments; but the dust from the non-gaseous mines of Gloucestershire and Somersetshire proved to be inexplosive agents. The experiment with this non-gaseous dust was repeated eight times, with the result that no explosive ignition could be produced.*

The only conclusion that could be formed from experience of an historical character, and from experiment up to date, was that the dust of these non-gaseous mines was harmless, and that the coal-dust theory had no application here.

The historical record of the non-gaseous mines was, however, broken, on November 14th last, by an accident at the Camerton Collieries, Somersetshire, which upon investigation proved to be an explosion. The only discoverable agent to produce the explosion was coal-dust, and it was surprising that neither experience nor experiment had given any indication of the danger. Manifestly a condition of insecurity existed, which necessarily must have been of recent development, as gunpowder shots similar to the one where this explosion was originated have been of constant daily occurrence for a great many years. Probably the two important changes at these collieries in recent years have been in the ventilation and the production of coal. Larger currents of air now pass through the ordinary roads at much higher velocities than heretofore. The output of coal has also been considerably increased; therefore the larger number of loaded trams in their progress from the coal-faces to the downcast shaft are swept by the

* Report made to the Royal Commission on Explosions from Coal-dust in Mines, by H. Hall, Esq., 1893.

opposing and accelerated currents of air. Coal-dust is consequently disengaged and deposited in the roads, and the air in passing over it evaporates the moisture and raises it to a dry and sensitive condition. The deposits of dust have, therefore, become greater in quantity and more sensitive in character in recent years, and these conditions have been progressively set up without any features to attract notice. The failure of the drastic tests to obtain explosive phenomena with the coal-dust of the district, only a few months before the explosion, would also naturally divert attention from the subject.

This explosion could not have been foreseen. It has, however, revealed the fact that coal-dust is an explosive agent, which was what the mining world and the public required should be demonstrated. It also provided the phenomena of an explosion produced by gases evolved from coal-dust. The author has investigated that phenomena, and hopes that the observations recorded in the following chapters will be an instructive contribution to the literature upon the question, and promote the elucidation of the danger, so that effective measures may be devised to remove a grave menace to life and property.

COAL DUST AN EXPLOSIVE AGENT.

DESCRIPTION OF THE CAMERTON COLLIERIES.

THE Camerton Collieries are situated in the Radstock district, on the north side of the Mendip Hills, about seven miles from Bath ; and work the coal under the Camerton Court Estate. The New Red Sandstone, and in some places the Lias and Oolite formations are partially developed, and are superimposed nonconformably upon the outcropping edges of the Coal Measures. The shafts pass through the New Red ground, and intersect the highest series of seams in the coalfield, which are worked here and at many other collieries in the neighbourhood ; and are known as the Radstock series. This series comprises six workable seams, named respectively, the "Great," "Top Little," "Middle," "Sliving," "Under Little," and "Bull" seams, which vary in thickness from 1 foot 6 inches to 2 feet 2 inches. These seams have been worked at the Camerton, and at other collieries in the district, about one hundred years, and extensive areas developed and worked. The extraction of the coal has necessarily caused the subsidence of the roofs of the seams over large tracts of the coalfield, so that the seams and their enclosing strata have been extensively tapped ; and fire-damp has never been discovered in either the coal faces, the goaves, or the faults. All these seams at the Camerton and the other collieries have been, and are still worked with candles or naked lights exclusively. The outcrops of the Coal

Measures and their faults being hermetically sealed by the superimposed New Red Marls and other strata of that formation, as well as more recent deposits, it is not possible that any fire-damp they may have contained could have escaped into the atmosphere, except through the colliery workings, where it must have been detected. Having regard to the magnitude of the aggregate workings of the collieries, and the manner in which the strata have been broken into, the only conclusion is that this series of seams is free from fire-damp.

The Camerton Court Estate is worked by two collieries, the "Old" and the "New," with separate working and ventilating arrangements. The underground workings are complicated by dislocating faults, which are common to the district, and necessitate a large extent of cross-measure drifts. The main faults approximate to the line of the upheaval of the Mendip Hills, being more or less of an east or west axis; but there are other subsidiary disturbances at varying angles. The seams are therefore displaced in an irregular manner, and intersected several times in the same horizontal plane. A sectional elevation of the seams and dislocations, as they were proved in the south cross measure drift from the downcast shaft of the New Collieries, is shown in Plate I., Fig. 1. One effect of these disturbances is that the main roads are, to a large extent, in solid strata; and as a rule they retain more moisture than those in the seams; and their own débris and dust are of an argillaceous and incombustible character.

The seams of coal frequently have a layer of comparatively soft material of an incombustible character, interposed between them and the hard roof, or underneath, between the coal and the floor, and sometimes dividing the coal itself, which is first cut out and placed in the goaf, and the coal is then easily extracted. The long-wall method of working is adopted, and, where the seam is hard the yield is mostly screened coal;

but, in any case the small coal is placed in the goaf. Until recent years, shovels were not allowed in the coal-faces, and only hand-picked coal was filled into the trams. Shovels are now used ; but the rule remains that no small coal must be sent out. As a part of the system to enforce care in excavating the coal, one end of the tram is left open, with simple tie-chains to keep the sides in their normal positions ; the lumps which are of cubical structure, are built as a wall in this end, and, properly speaking, there should be no small coal except that made by attrition in conveyance. In these circumstances, the deposition of dust in transit along the haulage roads ought to be nominal. The coal, however, varies in hardness, some small is filled into the trams, and the quantity is increased in the softer coal by jiggling the trams down inclines, changing at junctions and pass-byes, and by the ordinary conveyance to the shaft. An inevitable deposition, therefore, results along the route, both of small dust and of pieces of the raced-up load.

The roofs are all of a strong character, and have to be broken down with explosives to make height for the trams, the portion excavated in this way often exceeding the thickness of the coal. This débris, with the other waste matter in benching, exceeds the capacity of the goaves ; and, taking a period of twelve months, a proportion of one tram of spoil is conveyed to the surface to four trams of coal. There is also a leakage of small particles from the trams of débris ; and these, with the coal that falls between the rails, are trodden into fine dust by the ponies, and for the time become incorporated. The dust and débris in the newly-made roads is argillaceous and incombustible matter ; and the general result is that the dust of the mine is of an impure and somewhat ponderous character.

The explosion occurred at the New Collieries, where the seams are won by cross-measure drifts from the downcast and winding pit, at 314

yards from the surface, Plate I., Fig. 1. At 330 yards from the shaft, the Middle Seam is cut, and a district of workings opened upon it. At the time of the explosion, some men were engaged there, but were not affected by it; and, with the exception of an incident that happened to one of them, who, at the moment was in the cross-measure drift, further reference to this district is unnecessary.

The Great Seam is cut at 700 yards from the shaft, and forms the Horse Gug district.

The Top Little Seam is reached at 960 yards, the workings being termed "Tom's Road."

Faults intervene, and the Great Seam is again found at 1,082 yards, and this point is called the "Pump Corner."

The drift continues for a considerable distance, crossing faults and again cutting the Great Seam in the New Branch workings.

Returning to the Pump Corner, the Horse Road in the Great Seam goes off in an easterly direction for 560 yards, where it is displaced by the Top Little Seam, in which the Horse Road continues; and at 594 yards from the Pump Corner deep workings, known as Probert's Dipple are opened, and a cross-measure drift is driven south, cutting the Great Seam. The Horse Road ends at the South-East Incline, 758 yards from the Pump Corner, where rise workings are opened. At 140 yards up the incline, the Top Little Seam is displaced by the Great Seam, and the workings beyond are in that seam, and form the South-East Incline district. The Incline measures 365 yards, and the explosion originated about 56 yards below the top landing. At this landing a level road is driven in a continuous line in troubled ground for 60 yards, and is followed by a series of inclines, Nos. 2, 3, and 4, measuring 90, 70, and 70 yards long respectively, which reach the working faces. The workings from the down-cast shaft to these coal faces, the return air-way, and also

the connection between Probert's Dipple and the New Branch workings, are shown in Plate II, Fig. 2, together with the points specially named.

The collieries are ventilated by a furnace, and the plan of ventilation and coursing of the air are shown by arrows. The cross-measure drift from the downcast shaft is the Main Intake airway, and the first split is made at the Middle Seam, the remainder of the current, which is about 7,500 feet per minute, proceeding direct to the Pump Corner (passing communications with the Return airway at the Horse Gug, Tom's Road, and the Manhole), and thence along the Horse Road to Probert's Dipple, where a second split is made, 1,500 feet per minute being sent down the Dipple. The remaining 6,000 feet travel the South-East Incline and ventilate that district, returning by the workings on the south side, crossing over the incline about 66 yards from the bottom to a staple communicating with the Top Little Seam, and thence out to Tom's Road, on the Main Intake, where it is diverted into the Main Return by double doors.

The split at Probert's Dipple ventilates the New Branch workings, and returns back through the New Branch to the double doors at the Pump Corner, and is there conveyed to the air-crossing and into the return airway.

The ventilation was enlarged about eight months before the explosion by the erection of a new furnace, which considerably increased the air in circulation. The Intake and Return airways remained of the same sectional areas; consequently the larger circulation could only be obtained by accelerating the velocities of the currents. The resistances increasing as the square of the velocity, an increased volume of air effects a rapid progressional velocity in the current, resulting in greater evaporation of the moisture of the walls of the airways. The loaded trams meeting these accelerated currents would be robbed of more fine

particles, while the dust on the floor, when disturbed by the ponies' feet and the miners passing in and out, would be subjected to a gravitating action, causing the separation of the lighter portions and their deposition upon the surface of the floor. These effects would proceed in a gradual and almost unobservable form to the officials who are constantly examining the workings. It is only after an explosion when its origin is suggested to lie in coal-dust, and it is remembered that dryness and fineness of dust are stated to be essential conditions to constitute its danger, that the necessity arises for a comparison of the dust in these particulars at different periods of time. In non-gaseous mines like Camerton such a comparison would not arise. If coal-dust be now demonstrated to be itself an explosive agent, these observations of the dust and the effects of rapid ventilating currents become important.

The dust of the roads travelled by the explosion was not uniform in character in regard to fineness, purity, or dryness. The coal in the faces of the South-East district workings is free from the sweat and moisture that exudes from some coals, and is itself comparatively dry. The floor of the seam has the moisture common to all under-clays, and the roof, when broken to make height of road, is wet, and yields drops of water. The benching being in argillaceous matter, there is very little dust made in extracting the coal; and that becomes damp in the new roads contiguous to the working faces. When the faces have advanced, the newly-formed roads become dry under the action of the air-currents, the wet condition of the roof disappears, and dust becomes observable.

In describing the dust, the terms "damp," "dry," "very dry," and "fine," are used in a colloquial, and not in an exact, sense. By the term "damp," it is meant that, under slight pressure, the dust is sufficiently damp to cohere together and retain an impressed form. When possessing no appreciable cohesion, and of insufficient mobility to elude com-

pression, it is termed "dry." Some dust had absolutely no cohesion, but a mobility that caused it to slip through the fingers ; this is classed "very dry." The term "fine" applies to these degrees of dampness and dryness, and includes the range from impalpable powder up to that sized particle which will not naturally float in the air, but only rises from a few inches to a foot above its bed, when subjected to the action of highly-heated gases. The dust first appears after the loaded trams have been passing over the road for some time, when, by reason of their contents leaking out, and the ventilating current sweeping their exposed surfaces of coal, or débris, carrying off fine particles, a deposit begins. Where the trams of coal and débris are mechanically conveyed, the whole of the floor becomes covered with a mixed dust of coal and argillaceous matter ; and if there be no débris to send out, the dust is almost pure coal.

For twelve months before the explosion, the Great Seam workings of the South-East district had afforded sufficient room to gob all the débris they yielded, and coal only was conveyed down the inclines ; therefore, only coal-dust was deposited. The inclines were all worked as self-acting jigs ; there was no abrasion of the argillaceous floor, either by ponies' feet, or by men tramping ; and the coal-dust remained as pure as when deposited by the air-current. The dust on the floor of the inclines consequently contained more coal than obtained in any other part of the mine.

The No. 4 Incline, the first from the coal faces, was not dry, and had no appreciable quantity of dry dust. The dust on No. 3 Incline was dry, also that on No. 2 Incline ; but on the level road to the siding at the top of the South-East Incline, it was damp. Dry dust covered the siding, and the South-East Incline (where the floor was not hidden by falls) down to its bottom landing-stage. Where the shots were fired it approximated to pure coal, due to the fact that the roof had sagged down,

and the raced-up trams rubbing against it, crushed their coal, the resulting dust being carried off and deposited by the current. The landing-stage at the bottom of the South-East Incline is formed by cutting into the floor of the seam ; and at the end of the cutting, where it is deepest in the under-clay, there is a small yield of water. These inclines, as they were found after the explosion, are shown in plan and elevation in Plate III. Figs. 3, 4, 5, and 6 are the South-East Incline ; Figs. 7 and 8, the siding, level road, and No. 2 Incline ; Figs. 9 and 10, Nos. 3 and 4 Inclines.

The ponies travelled from the South-East Incline to the shaft ; and the dust between the rails throughout is chiefly under-clay, mixed with a little coal which falls off the trams, and is trodden into dust by the ponies' feet. Between the rails and the sides of the roads, fine dust prevails, of a brown and greyish black colour, probably composed of equal quantities of coal and débris. The ponies and trams exert a movement in the dust, which is increased by the air-current ; and the coal being the lighter material, is floated to the surface, and therefore occupies the most exposed position.

From the South-East Incline to Probert's Dipple, Plate IV, Figs. 17, 18, 19, and 20, the dust was damp. At the Siding, Figs. 19 and 20, there was the inevitable leakage, which increased the deposit ; and coal only was conveyed here, so that the dust outside of the rails contained more coal than débris. The dust in the dipple was also of this character.

From Probert's Dipple to the Pump Corner, Plate IV, Figs. 11, 12, 13, 14, 15, and 16, the dust was dry, and in some places very dry, where exposed to view between the falls. A considerable length of faulty ground, of a marly and friable character, is crossed, needing to be thickly timbered ; and where there was timber the dust accumulated more than

elsewhere. Between two heavy falls, the dust was impregnated with the pony droppings, in a dry and comminuted form, giving it a sensitive appearance and mobile feeling. The effects of the air-current here were conspicuous in absorbing moisture, and in effecting a gravitating action, in the light portions of the dust, bringing these particles of combustible matter to the surface.

In the New Branch (Plate V., Figs. 25 and 26) there was a little dust for the first fifty yards from the Pump Corner, which varied from damp to dry, and darker than that in the Horse Road. The loaded trams were exposed to sudden and violent pulsations of the air in passing through the double doors from the Return to the Intake, which probably caused a larger deposit of coal. Beyond the fifty yards the branch was damp. The entire traffic from the South-East, Probert's Dipple, Great Vein Branch, and New Branch districts converged at the Pump Corner and proceeded out the Main Intake. In this aggregate of produce the proportion of coal to débris was as four trams to one, and this débris was the only source of incombustible matter, as the floor of the intake was cross-measure ground, which does not yield to abrasion by the ponies' feet like the under-clay of the seams. This larger traffic was exposed to the unimpeded current of air direct from the downcast shaft, and dust was deposited on the floor outside of the rails resembling that in the New Branch in colour. From the Pump Corner to the Horse Gug (Plate V., Figs. 21, 22, 23 and 24) the conditions varied: in the first 156 yards dry dust prevailed; the following 53 yards was damp or wet, and the remaining 173 yards varied from dampness to dryness. The mechanical violence of the explosion terminated in the first length of damp and wet ground, and beyond that point there was no disturbance of any kind.

THE EXPLOSION.

THE South-East Incline district was worked in three eight-hour shifts, sixteen hours being occupied in coal-getting, and eight hours, from 8 p.m. to 4 a.m., in repairing and making roads. On November 13th last, William Hawkins, aged 32 years, and George Tarrant, aged 17 years, were sent into this district to blast the roof of the incline where it had sagged down, and make height for the loaded trams to pass under. Their work was to rip down $3\frac{1}{2}$ yards of roof about 56 yards from the top of the South-East Incline, and place the débris in an old road adjoining. They descended the shaft at 8 p.m., commenced the operation, and at midnight an explosion occurred, whose origin has been traced to the place in which they worked, and their lifeless bodies were found there about ten hours later. An examination of the place showed that the deceased men had accomplished a considerable portion of their task. They had bored and fired one hole, which had ripped the ground effectively, cleared away all the débris, and had bored and fired a second hole. The débris of the second shot was lying untouched on the floor of the incline, and it was evident from its limited quantity that the explosive had failed to break down its burden, and that practically it was a partially blown-out shot. The bodies were burnt; violence had been developed over one mile of roads, and the doors and a crossing were found shattered, all presenting the phenomena of a gaseous explosion. It was inconceivable that any mechanical relation existed between the charge of explosive in No. 2 shot and the destruction wrought. Fire-damp

was known to be non-existent; therefore the character of the agent that had caused the phenomena remained to be discovered.

The explosion appeared to be inexplicable; coal-dust was undoubtedly present; but it was believed, and with good reason, to be innocuous, and there was no reasonable theory upon which it could be supposed that the violent disruptions witnessed through a mile of workings could have been initiated by the ignition of three-quarters of a pound of gunpowder. The first step in the solution of the mystery was the preparation of records and plans of the circumstances and the phenomena of the explosion, and these will now be given in detail, that features common to other explosions may be discerned, and the foundation established for the conclusions to be drawn.

Returning to the seat of the explosion. The boring tools, the canister with a little powder in it, and the deceased men's shirts and food-bag were found in No. 2 Refuge hole, their candlesticks in No. 4 Refuge hole, and their bodies 19 yards beyond (Plate VI., Figs. 27 and 28). On the north side of the Incline there was a bank of débris rising in a slope from the rail to the side wall, and covered with dust (Plate VI., Figs. 29, 30, 31 and 32). It was of increased width where the shots were fired, and extended on to the side wall a short distance below No. 2 shot; then curved back towards the rail at the timber prop H (see Plate VI., Fig. 32). Opposite No. 2 shot, and measuring from the rail, the bank is 2 feet 9 inches, and in the bend at the prop it is 4 feet wide, where it gains a height of 2 feet at the side wall. The two holes were bored with a rotary hand-drill from the lower side, at declivities of 17° and 27° respectively, and obliquely to the Incline, to cross the cleavage and effect lateral rupture. The angles and declivities of the holes caused their axes in extension to strike the bank referred to. The explosive in No. 1 shot effected considerable forward and lateral rupture, in which its products

were scattered. The resistances of the stemming consequently exceeded the resistances in these lines of rupture, and barred the projection of the products of the explosive along the axis of the hole towards the bank. The lines of rupture approximated to a horizontal plane, the displaced strata feathering out in the sides and front, and the products of the explosive, therefore, struck the side walls of the Incline and were extinguished. The conclusion from the examination and measurements of No. 1 shot was, that its explosive had no effect on the dust of the bank or on the floor of the Incline.

The débris of No. 1 shot being cleared away, the deceased men fixed the prop G, Figs. 27, 28, and 31, to which they attached their boring machine, and bored No. 2 hole, whose axis in extension intersects the bank at a distance of 8 feet, see Fig. 31. At this point, the bank is increasing to its maximum width, and in form presents a favourable receptacle to retain any matter projected into it. The small extent of ground ripped by No. 2 shot, is shown in Figs. 29, 31, and 32, which also indicate the lines of rupture laterally and in front. A transverse joint crossed the roof in front of the hole, Fig. 31, barring its development forward; on the south side it ripped out to a thin edge; but on the north side it broke with a sharp declivity. The form of rupture, and the quantity of débris, show that the resistances of the strata intended to be dislodged exceeded the resistances of the stemming, which was therefore expelled from the hole. The result was that a portion of the products of the explosive was projected into the bank, where the dust was in a favourable condition for distillation, and the investigations now began to yield the suggestion that coal-dust may have been a factor in the explosion.

No. 2 shot hole measured only 10 inches in length, and it was difficult to understand why the deceased men had fired such a short hole,

especially as they had previously bored No. 1 hole 21 inches. An examination of the roof showed that a long hole had been fired at some time previously, 18 inches in front of No. 2 hole (see Fig. 31), and the suggestion arose that it may have been the shot first fired that night, and that its rending effects had entered into the calculations of the deceased men in fixing and firing No. 2 hole. In comparing these holes, they proved to be of different diameters; and the former had been bored by percussion, for which there were no tools in the place; whereas No. 1 shot corresponded with No. 2, in gauge and in other features, showing they had been both bored that night and with the rotary drill found in No. 2 Refuge hole. The deceased men could see this old shot hole, and may have thought that it had already shaken its adjacent strata, so that if they placed No. 2 hole near thereto, their work of ripping the roof would have been completed; forgetting that, in the lapse of time, the roof had sagged down, locking the earlier disruptive effects, and keying the strata beyond its natural strength. It is reasonable to assume that Hawkins, who was a practical miner, examined the roof before deciding upon No. 2 shot hole, and that he had reasons for not boring it further into the bridge of stone (Fig. 31) which he sought to break down. It is more than probable that he saw the joint crossing the incline in front of his No. 2 hole, and knew that if the end of the hole approached near to it, the explosive would be dissipated, and the bridge of strata left unbroken. His object probably was to leave as much stone between the root of his hole and the joint, as would protect his charge from wasting, and to make the charge heavy enough to burst through joint and bridge. He started the hole $14\frac{1}{2}$ inches in front of the joint, and after boring 10 inches probably assumed that he had left $4\frac{1}{2}$ inches between them. His calculation was upset by the fact that the joint haded towards him 32 degs. from the vertical as it rose into the roof, reducing the dis-

tance between it and the hole to $3\frac{1}{2}$ inches, and presenting an oblique face to the shot, which deflected the force of the explosive, letting it off at a tangent. It was not possible to foresee this condition of the joint ; and Hawkins loaded his hole, intending, without doubt, to break through the bridge, greatly overcharging it for its ordinary scope. The object was only partly accomplished, and the heavy charge, on being fired, largely escaped into the Incline.

Gunpowder was the explosive used, and was carried into the mine loosely in tin canisters holding about $2\frac{1}{2}$ lbs., under an authorisation from the Department of the Home Office, being an exemption from the ordinary course permitted by General Rule 12 (b), which presupposes the absence of fire-damp, or special danger. A needle was found with the boring tools, and it is therefore probable that Hawkins fired his charges with squibs, which was a common practice.

The upper halves of the walls of the two holes bear the radial mould of the rotary drill, and offer some evidence as to the quantities of powder with which they were charged. Measuring from the root of No. 1 hole, the first $7\frac{1}{2}$ inches of the wall was dark with the stain of the powder, showing that it had been charged to that depth. The radial impression of the drill-bit was then abraded, marking the commencement of force in the stemming ; and the remainder of the hole was stained with the grey colour of the clay, or marl, used for stemming. This hole, therefore, contained $7\frac{1}{2}$ inches of gunpowder, equal to $13\frac{1}{4}$ ounces ; and assuming that the canister was full when the deceased men commenced the shift, there were $26\frac{3}{4}$ ounces left when they started No. 2 hole.

The radial mould was also distinct on the upper wall of No. 2 hole, and, measuring from the root of the hole, the first $4\frac{1}{2}$ inches were dark with the stain of the powder ; the next $2\frac{1}{2}$ inches were a shade lighter, and the remaining three inches were grey, corresponding with the

colour of the stemming. The radial impression was perfect in the first two portions of $4\frac{1}{2}$ and $2\frac{1}{2}$ inches, making 7 inches from the root of the hole ; then abrasion commenced, and the mould was crushed and broken. This abrasion marks the commencement of pressure in the stemming. In a shot of this character, with a heavy burden to batter down, and with a hole of such a sharp declivity, it was essential to first insert a small quantity of stemming, to press the charge home and secure it. If it be supposed that the middle $2\frac{1}{2}$ inches of the hole were occupied by stemming, that $2\frac{1}{2}$ inches of compressed marl would fill at least 4 inches when first inserted, which necessitates the conclusion that Hawkins filled 4 inches of stemming next to the charge, before using force with his stemmer to compress it. An experienced miner like Hawkins would not do such a foolish thing ; he knew what he was attempting to accomplish, and the importance of the charge being well pressed home in the root of the hole, and compressed there as closely and firmly as possible. To effect this, he would insert small quantities of stemming at a time, and compress each portion separately, to expel the air, fill the hole tightly, and effect the greatest possible resistance between the stemming and the walls of the hole, to prevent its expulsion when the charge exploded. There can be but one conclusion that the abrasion of the impressions on the wall of the hole, 7 inches from its root, fixes the first application of force in stemming, and, therefore, the outside end of the charge of gunpowder. This leaves only 3 inches for stemming, which confirms the suggestion that Hawkins counted upon the strata being dislocated and shaken by the old shot, and expected to secure that advantage by placing his shot so close to it ; that, in fact, he considered the bridge of stone had been dislocated, on the upper side down to the joint, by the old shot, and a battering charge against the joint from the other side would complete the disintegration.

This makes the charge in No. 2 hole, 7 inches, equal to $12\frac{1}{2}$ ounces of powder, forming, with the $13\frac{1}{4}$ ounces in No. 1 hole, $25\frac{3}{4}$ ounces, and leaving a margin of $14\frac{1}{4}$ ounces in the canister, provided it was full at the commencement of the shift. Hawkins was a practical miner, experienced in the work of blasting the roof of the Great Seam with gunpowder. He had received instructions as to the extent of the work he had to do upon the roof of the Incline; and it is unreasonable to suppose that he would commence the duty with less than 2 lb. of gunpowder in his canister: with that quantity there would be $6\frac{1}{4}$ ounces left after his two shots had been supplied.

Three-quarters of a pound of this explosive was not an excessive charge for the work Hawkins intended to accomplish, but it bore no proportion to the actual result. The hole was started in a face of stone about 8 inches deep, which was broken down; the lateral ripping thinned out in about 2 feet on the south side, and broke down abruptly at 18 inches on the north side; while the forward ripping ended at the joint, $3\frac{1}{2}$ inches in front of the hole, and in all about 60 lb. of stone was dislodged.

On the north side of the Incline there was a vertical joint, running parallel with the Incline and distant 6 feet laterally from No. 2 shot hole, which cut off a large stone in the roof of a prismatical form. The face of the stone in the joint was 3 feet 6 inches wide and 16 inches deep, and it extended out into the Incline 3 feet 6 inches, tapering irregularly to a face 12 inches wide and 3 inches deep, and joining the strata ruptured by the shot. This stone was shaken down, and fell on the rail (see Plate VI.), Figs. 29, 31, and 32. It was beyond the scope and reach of No. 1 shot, and was, no doubt, locked in its position in the roof when No. 2 hole was being bored. The relative positions of these two shots show that Hawkins had, in a practical manner, broken down the strata which

was ruptured by No. 1 shot, before commencing to bore No. 2 hole. In doing so it is reasonable to assume that he sounded this stone, and found it firm enough to be safe, otherwise he would not have worked underneath its hanging end, as he did do, when he charged No. 2 hole. This stone, weighing between three and four hundredweight, was out of the range of both shots, and its dislodgment is evidence of violent concussion, occasioned by No. 2 shot.

In the upper wall of No. 2 hole there is evidence that it contained a large charge of gunpowder; the violent concussion that dislodged the block of stone shows that the energy of the explosive shook the roof of the incline in its attempt to batter down the bridge of stone; and the forward burrowing of the charge, the forms of rupture in the stone, and the small quantity of strata displaced, indicate that the gunpowder was overburdened, and that its products were driven into the dust on the bank and floor of the incline. The facts are now clear that dry coal-dust was present where the deceased men worked; that they bored and fired No. 1 hole without any unusual effect upon the dust; that in a subsequent period of about one and a half hours (in which the dust set up would subside or be carried away in the air-current) they broke down the ruptured and shaken stone, removed the débris, and bored and fired No. 2 hole: and the products of its explosive were driven into the coal-dust. The occurrence of a partially blown-out shot in the presence of coal-dust is therefore established.

The explosion presents explosive phenomena of an intermittent character, there being a succession of spaces of violent disturbance, separated by periods of mechanical inaction. These spaces, which contain exhibitions of violence and presumably the *loci* of explosive forces, will be numbered as explosions at this stage of the enquiry, for convenience of reference.

Proceeding up the Incline, the first indication of disturbance is at a distance of 116 yards from the shot, at the bottom of No. 2 Incline, where some timber had fallen ; but at a distance of 136 yards from the shot, a 12-inch wrought-iron air-pipe, used as an air-crossing, is rent and broken in irregular form, exhibiting evidence of explosive violence, and will be termed No. 1 Explosion, Plate III., Figs. 7 and 8. This pipe presents an appearance like that which would ensue if some cartridges of dynamite had been secured upon it and exploded. It was made of sheet-iron one-sixteenth of an inch thick, and lightly secured in position next to the roof ; consequently, it would yield bodily by displacement, or collapse, if exposed to any ordinary gaseous pressure, or if distant from a centre of explosive violence. Its condition indicated that it had been subjected to an immediately adjacent external detonating explosion. Some timber fencing, at a staple 27 yards from the pipe, was displaced ; the roof of the Incline for 43 yards was slightly scaled ; and thin scales, of 1 and 2 inches in thickness, were lying upon the floor.

At the bottom of No. 3 Incline, 206 yards from the shot, a door in the south level measuring 4 feet by 3 feet 10 inches, and distant 5 yards from the Incline, was broken and blown inwards. Two trams of coal were on the landing, with their closed ends exposed to the advance of the explosive gas ; one was driven 3 yards up the Incline and fixed there ; the other was twisted and violently thrown across the Incline under the rope wheel, and its contents scattered on the floor. (Plate III., Figs. 9 and 10, No. 2 Explosion.)

In the following 70 yards there was slight scaling of the roof, but at the bottom of No. 4 Incline a door, 4 feet by 3 feet 10 inches in the south level, and distant 4 yards from the Incline, was driven inwards and the frame broken. Two full trams of coal were standing on the landing ; one had been driven up the Incline, and pulled backward on its end, the

other was thrown across the Incline under the rope wheel, and the contents of both were scattered over the floor. (Plate III., Figs. 9 and 10, No. 3 Explosion).

The positions of the four loaded trams of coal at the bottom landings of Nos. 3 and 4 Inclines were confusing. The two on the right side appeared to have been seized, violently twisted and twirled about, and thrown under the rope wheels. The two on the left side were driven direct up the Inclines ; one was left standing fast on the rails, the other tipped backward on its end. The Inclines are worked in pairs and the horizontal jig wheels are fixed above the trams ; the ropes are therefore high off the floor, and slightly strained. It is difficult to imagine that a wire rope with a convex surface, and freely suspended, could be set in violent movement by a gaseous explosion, but it was evidently subjected to a force, similar in character to that at the air-pipe below. The trams were standing on parallel lines of rails on their respective landings, and presented equal surfaces to the explosive force. The two on the left side were probably released from their ropes, and yielded to the force driving them up the Inclines. The two on the right side were possibly attached to their ropes, which were thrown into violent movement, and in this way the unequal and distorted positions may have been produced.

A singular phenomenon occurred at the bottom of No. 4 Incline, where the door and part of the frame in the south level were found driven into the level ; while the remainder of the frame was found in the Incline.

The violent effects at these suggested centres of explosive violence are limited to their immediate vicinities. At No. 1 Explosion, the air-pipe is the evidence of this action. At No. 2 Explosion, all the disturbance is within a radius of 4 yards ; and, at No. 3 Explosion, in a radius of 3 yards. (The scaling of the roof could not have been effected by mechanical force, and the cause must be sought in another direction.)

The explosion terminated in this direction at the bottom of No. 4 Incline, where the natural moisture of the roof had not dried up, and the dust practically ceased.

Returning to the South-east Incline, the first explosive violence occurred below the centre wheel, about 140 yards from the shot, and 55 yards of the Incline were wrecked with falls from 3 feet to 9 feet high above the timber and ordinary roof. (See Plate III., Figs. 3 and 4, No. 4 Explosion). The centre wheel is fixed in a heavy wood frame, which is firmly secured near the roof, the whole weighing about 10 cwt. This structure was moved down hill contrary to the direction of the suggested explosive force; and for 55 yards above the wheel in the direction of the shot occasional props were displaced, the roof sometimes scaled, and the props carrying the rope guide pulleys were found lying several feet down the Incline, also against the explosive force. The positions of the frame and pulley props suggested that some force had acted from the upper side, but the bodies of the deceased men were lying near, and had suffered no violence, so that there could not have been any explosive force there. The wire rope which works the Incline was coiled round the centre wheel, and the two ends were lying extended at the top and bottom landings of the Incline, 365 yards apart, and resting upon the guide pulleys *en route*. If it be supposed that the suggested effect upon the rope in Nos. 2 and 3 Explosions was repeated in No. 4 Explosion, and that that effect was increased by the falling timber there entangling and shortening the rope, and the crush of the falling roof be added, the result would be a violent jerk, effecting a sudden tug upon the centre wheel, pulling it down the hill. This violence would be transmitted by the rope to the guide pulley posts above, displacing and drawing them towards the wheel in the positions in which they were found.

No. 4 Explosion greatly exceeded its numerical predecessors in violence and in extent, and was also followed by a period of mechanical inaction. At the lower end of its fall there are 26 yards of the Incline timbered with posts and collars in similar form to that portion which was wrecked, but this timber was not disturbed (Plate III., Figs. 3 and 4).

The remainder of the Incline, measuring 84 yards, was timbered in like manner, and, with the exception of four sets, the whole was displaced, the roof falling for a height of from 3 feet to 9 feet above the collars (Plate III., Figs. 3 and 4, No. 5 Explosion).

The roof of the Incline from the wheel to its lower end was more or less of a friable character for several feet in thickness, necessitating post and collar timbering. In roads needing such support the mechanical effects of an explosion are necessarily much more extensive than those where the roof is firm, requiring only occasional props. In inclines the timber is fixed approximately at right angles to the inclination of the strata, therefore hading from the vertical, and is secured in that position by wedging and the weight of the strata upon it. If any force acts upon this timber, deflecting the upper ends of the props from their positions, or releasing the wedging and keying, they fall to the floor, and the incline collapses. It is not difficult to understand how the concussion of an explosion in an incline may produce a movement in the loose roof and in the timber supporting it, releasing the wedges and keys, and allowing both timber and strata to fall. Such a concussion will account for the falls under notice, and the fact that four sets of timber remained standing in the fall of No. 5 Explosion shows that they were locked in position, possibly by some large beds of stone.

The centres of Nos. 1, 2, and 3 Explosions could be localised because of their limited action; but where the effects are extensive, as in Nos. 4, 5 and some of the succeeding Explosions, it is difficult to fix this point.

The conclusion formed from the examinations was, that the centre of No. 4 Explosion was in the early part of the fall next to the centre wheel, and that the end of the fall marks the limit of its concussive force. The roof of the Incline near the bottom landing was strong bedded stone, and its dislodgment demanded great force, suggesting that the explosive violence was localised in its intensity about this point, which would place the centre of No. 5 Explosion, in the lower end of the Incline, less than 20 yards from the Horse Road.

In the Horse Road, at 14 yards from the Incline, a little timber was displaced (Plate IV., Figs. 19 and 20), probably by the concussion of No. 5 Explosion, and had the adjacent timber been less firmly secured it must have fallen also. The timberings in level roads, however, had their posts fixed vertically, therefore, it is in a much more stable position than that on Inclines; it rarely falls when simply unkeyed, and will admit of extensive deflection before collapsing. The timber near the Incline, excepting the two sets referred to, retained its position.

Proceeding from the South-east Incline, along the Horse Road, the trams of coal were standing on the rails in the siding (Plate IV., Figs. 19 and 20) where they had been placed at the end of the evening shift, and for a distance of 164 yards, to Probert's Dipple, the road was practically intact and had not been subjected to mechanical violence. At this point there had been a great disturbance. In Probert's Dipple, and extending a distance of 100 yards from the Horse Road, there were occasional slight falls of roof. In the Great Vein Branch, No. 1 door, 4 feet by 3 feet 10 inches, and distant 12 yards from the Horse Road, was shattered to fragments, and the intervening roof was broken down. No. 2 door, of the same dimensions and fixed in the branch, 80 yards from No. 1, was driven further away. The Horse Road presented the following phenomena in succession for 66 yards:—

Strong cliff, roof ripped 2 feet high	....	....	....	25	yards
Timber down, roof scaled	....	....	....	9	„
Fall, 10 feet high in the centre above the timber (faulty ground)	....	....	....	8	„
Timber standing	....	....	....	8	„
Fall, 6 feet high over the timber (faulty ground)	....	16	„		

(See Plate IV., Figs. 17 and 18, No. 6 Explosion.) At both extremities of this disruption, the Horse Road was in its normal condition. The explosive force was probably ignited close to the Great Vein Branch, and spent itself in the disturbances described.

From the outside fall of No. 6 Explosion, there was not any exhibition of violence in the Horse Road for a distance of 343 yards. In an intervening space of 34 yards, the timber was displaced and the roof scaled 1 and 2 inches in thickness (Plate IV., Figs. 15 and 16); but there was no correspondence between these effects and the effects exhibited in the seats of the explosions; and, consequently, they must have been due to causes other than explosive violence.

This long space of inaction was followed by No. 7 Explosion, which was of great violence and of considerable extent. The Horse Road was more or less wrecked for a distance of 119 yards, and presented the following condition (Plate IV., Figs. 11 and 12):—

Fall, 8 feet high in the centre over the timber (faulty ground)	8 yards
Timber props displaced, roof scaled	12 ,,
Timber displaced, jointy cliff roof ripped 3 feet above the collars	18 ,,
Timber displaced, little débris down	8 ,,
Strong bedded stone ripped 3 feet to 4 feet high	16 ,,
Fall, 21 feet high over the collars in the centre	21 ,,

Timber displaced, little débris down ....	....	....	14 yards
Sundry stones dislodged from roof and side ....	....	....	10 ,,
Rise side displaced, filling the road with débris ....	....	....	12 ,,

The maximum violence was probably exerted near the centre of this wreckage, where the strong bedded stone was ruptured, and the mechanical force was again expended in the dislocations named.

There had not been any disturbance in the remaining 66 yards of the Horse Road, between the last débris of No. 7 Explosion and the Pump Corner, but violent action was again set up in the Main Intake there, making No. 8 Explosion. The entrance to the New Branch at the Pump Corner is barred by double doors; No. 1 door forms practically an extension of the side of the Horse Road; No. 2 is 11 yards distant in the Branch. These doors are 5 feet 2 inches by 3 feet 10 inches, and made of 1-inch pine, with three battens 6 inches by 1 inch, and are hung to oak frames, 5 inches by $4\frac{1}{2}$ inches, by iron hinges, $2\frac{1}{2}$ by $\frac{1}{2}$ -inch, secured on the battens with $\frac{1}{2}$ -inch bolts and nuts. They are fixed on the outside of the frames, and kept closed by the Main Intake air-current. Immediately in front of the Horse Road, and on the side of the Main Intake, there was an elm tool-box, $3\frac{1}{2}$ feet long, 16 inches wide, and 18 inches high, which at the time of the explosion contained some heavy tools and an empty powder canister. There was also an empty train standing on the line of rails leading into the New Branch, inside of the Horse Road points, and probably near to No. 1 door. In the Main Intake, 11 yards outside of No. 1 door, there was an air-crossing in the roof, with brick side walls and timber floor carrying the return air from the New Branch workings. These fixtures and materials are shown in Plate V., Figs. 25 and 26.

All these fixtures and materials were found broken after the explosion. Nos. 1 and 2 doors were shattered into fragments scarcely large

enough for firewood, and scattered into the New Branch. The hinges were torn away from the doors, and the hooks from the frames, and also hurled into the New Branch. The hanging sides of the door frames were rent and splintered through the hook holes and driven in the same direction. The empty tram was found 5 yards inside the first door, bulged and crumpled, with bent axles, so that it would not travel on the rails, and had to be carried away. At 30 yards from No. 1 door, the post and collar timbering in the New Branch was displaced for 20 yards, and the roof had fallen for from 12 inches to 2 feet in height. The air-crossing in the Main Intake was blown upwards and the bricks scattered. The tool-box was shattered to bits, excepting the bottom on which the tools rested, and the powder tin was crushed.

There is no difficulty in localising the ignition of the explosive gas here in the Main Intake, outside of the tram, but near to it; and it is significant that with a loose and free end towards the downcast shaft, and an open end in the Horse Road, there was such an exertion of force upon the tram, the box, and the doors, and for 50 yards beyond in the New Branch. This exhibition of violence extends 61 yards; where it ceased in the New Branch there was no dust, the floor was damp, and the atmosphere was the return air of that district; in the opposite direction it ended at the air-crossing.

The Main Intake had no evidence of any disturbance in the 66 yards from the air-crossing to the Manhole, where explosive violence is exhibited of a limited extent (No. 9 Explosion). The roof of the Intake was thick bedded stone, but supported with props. The communication with the Return here was a small airway approximately at right angles to the Intake, rising at an inclination of 30 degs. with the horizon. The entrance was barred at the side of the Intake by a manhole door, 2 feet 6 inches square, hung to a frame of the ordinary form, with

iron hinges one and a half inches by three-eighths, and upon the Intake side (Plate V., Figs. 23 and 24). The explosion, though limited, was violent; the timber props were displaced, and the stone over them ripped to a height of 3 feet for 4 yards in the Intake. The door was broken into small bits, which were scattered on the floor of this steeply-inclined airway for 30 yards from the Intake; the hinges were torn from the wood, one was broken clean through a bolt hole, and both also driven into the airway.

The mechanical violence of this explosion was limited to a radius of 3 yards; and the positions of the hinges and fragments of the door place the ignition opposite the manhole. This concentrated violence occurred in the Intake with loose ends in both directions, for the dissipation of the explosive energy. Another space of mechanical inaction followed between the manhole and Tom's Road, over a distance of 38 yards, and there again destruction ensued (No. 10 Explosion). Tom's Road is at right angles to the Intake, and the roof of both is thick bedded stone supported by props. Double doors are fixed in Tom's Road, No. 1 at 7 yards from the Intake, No 2 10 yards beyond (Plate V., Figs. 23 and 24). These doors were of the same dimensions and strength as those in the New Branch at the Pump Corner, and hung in like manner on the outside of the frames, having the weight of the Intake current upon them. The frames were stronger, being 6 inches square. The Intake presented the following appearance for $75\frac{1}{2}$ yards:—

Opposite Tom's Road, props displaced, and stone

bedded roof ripped 3 feet 6 inches above them for $8\frac{1}{2}$ yards

Stone archway undisturbed „ 18 „

Fall in underclay ground, 12 feet above the timber

in the centre „ 12 „

Stone ground, without timber, undisturbed „ 30 „

Fall in friable marly ground, 6 feet above the timber

in the centre for 7 yards

In Tom's Road the props were displaced and the roof ripped, filling the road between the Intake and No. 1 door. The two doors were driven through their frames, shattered into bits, and distributed over the floor of Tom's Road, for a distance of 50 yards from No. 1 door. The first door-frame was left standing, ripped up through the hook holes. The lintel and hanging side of the inside frame were displaced; the former was uninjured, the latter was shivered into matchwood and scattered along the road. The iron hinges, of a section of $2\frac{1}{2}$ by $\frac{1}{2}$ inch, weighing about 14 lb. each, and secured to the doors by four $\frac{1}{2}$ -inch bolts and nuts, were wrenched from the woodwork; two were found 20 yards inside the second door, one broken off short through a bolt hole, the other bent into a semicircle.

This No. 10 Explosion greatly exceeded No. 9 Explosion in its extent and violence, and apparently was of greater energy than No. 8 Explosion. The ignition of the explosive mixture probably occurred in the Intake at its junction with Tom's Road; and here again the generated energy was effective in mechanical destruction, both in the Intake and at right angles to it, though it was, comparatively speaking, unconfined.

Inside the doors of Tom's Road, the floor was covered with very dry dust, but there was no propagation of the explosion in that direction. The atmosphere there was the return air from the South-east Incline district. Wet and damp ground occurred in the Intake outside of Tom's Road, in which the propagating potentiality of the gases was broken down. The Explosion had now been propagated against the Intake air from the shot to Tom's Road, a distance of 1,191 yards, and the damage had extended to the fall at 1,278 yards, but there was no trace of violence beyond, and it is important to consider the features of the

Intake airway, where the remarkable vitality of the explosion was extinguished. Commencing at No. 10 Explosion, at Tom's Road, the following conditions obtained:—

Archway and Fall, floor and sides dry and dusty	... 30 yards
<hr/>	
Water and mud on floor; no dust	... ... ... 22 yards
Floor damp between the rails, damp dust outside of the rails	.... .... .... 8 ,,
Last Fall, floor and sides damp, no dust	... ... 7 ,,
Water and mud in floor, sides wet, no dust	... ... 16 ,,
	<hr/> 53 yards.
Floor damp between rails, intermittent wet spots, dust outside of rails damp to dry	.... .... .... 78 yards
Floor and sides damp and muddy	.... ... ... 8 ,,
Floor and sides dry and dusty to Horse Gug...	.... 87 ,,
	<hr/> 173 yards.

There is no distinct evidence to show how far the heated gases travelled outside of Tom's Road. They would, undoubtedly, pass through the first 30 yards of dry and dusty ground, continuing the chemical activities they had evoked in antecedent sections, and would reach the 53 yards of damp, wet, and dustless ground, with the products of those activities at a high temperature. These products and the heated generating gases that produce them, would inevitably surrender heat by impinging upon the damp and wet surfaces to which they were now exposed. The water would be converted into steam at the expense of the gases and products, and their heat would be exhausted if the surfaces of contact were sufficiently large, and their inter-actions of adequate duration. The nature and extent of the activities set up by the gases and products in their contact with water, would, as regards propagation, be the reverse of their action in the coal-dust, and the rapidity with which they would part with their heat would

depend upon the facility with which they would undergo condensation in such circumstances. The condition of the Intake, for some distance outside of the 53 yards of damp and wet ground, was not unfavourable to the chemical activities that prevailed in preceding sections of the workings; but the propagating gases had been so reduced in temperature in the wet ground, that they had insufficient residual heat to ignite the explosive gases produced in the first 30 yards from Tom's Road, and the wet floor and absence of dust precluded any supplementary source of heat from which ignition could be obtained, so that propagation ceased, and the heat and gases that remained died away in the Intake air.

The exhibitions of mechanical violence produced by the several explosions may be conveniently summarised by tabulating the suggested centres of explosive action, or the points where the ignitions of the explosive mixtures were probably determined; the distances covered with the débris of mechanical disturbances; and the intervening spaces of mechanical inaction. The suggested centres of ignition of the explosive gases are:—

From No. 2 Shot to No. 1 Explosion, with the air

		current	136 yds.
„	No. 1 Explosion to No. 2	„	70 „
„	No. 2 „ No. 3	„	70 „
„	No. 2 Shot to No. 4	„ against the air	
		current	140 „
„	No. 4 Explosion to No. 5	„	150 „
„	No. 5 „ No. 6	„	164 „
„	No. 6 „ No. 7	„	460 „
„	No. 7 „ No. 8	„	134 „
„	No. 8 „ No. 9	„	78 „
„	No. 9 „ No. 10	„	45 „

The lengths of road over which the explosions exerted more or less destruction, and the intervening spaces where no violence occurred are :—

	Limits of destruction.	Intervals with no violence.
No. 2 Shot to Air-pipe, No. 1 Explosion		136 yards
No. 1 Explosion, Air-pipe and Fencing....	27 yards	
Interval... 		43 ,,
No. 2 Explosion. Trams and door	... 8 ,,	
Interval... 		66 ,,
No. 3 Explosion. Trams and door	... 6 ,,	
No. 2 Shot to Fall, No. 4 Explosion	...	130 ,,
No. 4 Explosion. Fall	55 ,,	
Interval 		26 ,,
No. 5 Explosion. Falls.... 	84 ,,	
Interval 		164 ,,
No. 6 Explosion. Falls in Horse Road	66 ,,	
Slight damage in Probert's Dipple		
for 100 ,,		
Doors in Great Vein Branch	... 92 ,,	
Interval		343 ,,
No. 7 Explosion. Falls 119 ,,		
Interval		66 ,,
No. 8 Explosion. Air-crossing doors		
and fall in New Branch 61 ,,		
Interval		66 ,,
No. 9 Explosion. Fall 4 ,,		
Interval		38 ,,
No. 10 Explosion. Falls 75 $\frac{1}{2}$,,		

The foregoing phenomena establish the fact of a gaseous explosion having been originated in the vicinity of gunpowder shots, and propagated 279 yards with the air-current, and for 1,278 yards against it. The problems to be solved are the initiation and propagation of this explosive phenomena.

INITIATION OF THE EXPLOSION.

THE origin of the explosion has been localised at the shot-firing in the South-east Incline. The blasting of the roof at that point was the only work in progress in the district, and the deceased men were exclusively engaged there. If inflammable gas had been present, it would have been previously ignited by their naked lights, and by the "Match" or touch-paper which was necessarily fixed upon the roof of the Incline to light the shots. The air-current was unimpeded by any movement of the trams or otherwise, and would sweep away any imaginable accumulation of an inflammable character in the period between the lighting of the "Match" and the explosion of the gunpowder. After lighting the "Match" the deceased men travelled to the windward side: the air-current had therefore to pass their naked lights on its way to the shot, and if any inflammable gas had been brought up, it must have been detected by their lights. The presence of inflammable gas is therefore absolutely precluded at this critical moment, and neither before nor since the explosion has there been a trace of such a gas in the Collieries. The only initial source of heat was in the products of the exploded gunpowder; the exclusive agent present from which explosive gases could be obtained was coal-dust: and these products were driven into the coal-dust. The first question therefore to be considered, is the nature of these products of exploded gunpowder, and their effects upon the coal-dust.

An elaborate series of experiments with "Fired gunpowder" were made by Sir Frederick A. Abel, F.R.S., and Captain Noble, F.R.S.,

in 1874 and again in 1880, which were communicated to the Royal Institution, and published in Vols. 165 and 171 of the "Philosophical Transactions." The object of the experiments was stated to be "To ascertain the products of combustion of gunpowder fired under circumstances similar to those which exist when it is exploded in guns or mines."* Several grades of gunpowder were used, including "Fine," "Pellet," "Pebble," and "Mining." The samples were subjected to analysis and their compositions determined. The temperature of ignition, and the bodies which formed the products of combustion were ascertained, with their percentage, weights, and volumes.

The mining powder upon analysis yielded the following bodies :—†

Saltpetre	....	....	....	....	61.66
Potassium Sulphate	....	....	....	....	.12
„ Chloride	....	....	....	....	.14
Sulphur	....	....	....	....	15.06
Charcoal	Carbon	....	....	17.93	
	Hydrogen	....	....	.66	
	Oxygen	....	....	2.23	
	Ash	....	....	.59	
Water	....	....	....	....	1.61

The products of combustion were of a mixed, gaseous, and solid character, and the proportions varied; the small grain powder yielding a decidedly smaller proportion of gaseous products than the larger grain. The products of the mining powder are given as follows :—‡

Proportion by weight of total gaseous products	·5135
Do. do. solid do.	·4704
Water	·0910
	—
	1.0000

* "Philosophical Transactions," Vol. 165, p. 61. † Vol. 171, p. 218. ‡ Vol. 171, p. 279.

The constituent bodies of these products were determined, viz. :—*

“ Percentage composition by volume of gaseous products,”

Carbonic Anhydride	....	....	....	32.15
Carbonic Monoxide	....	....	....	33.75
Nitrogen	....	....	....	19.03
Sulphydric Acid (H_2S)	....	....	....	7.10
Marsh Gas (Methane)	....	....	....	2.73
Hydrogen	....	....	....	5.24
				<hr/>
				100.00

“ Percentage composition by weight of solid residue,” †

Potassium Carbonate	....	....	....	41.36
“ Sulphate	....	....	....	.59
“ Monosulphide	....	....	....	37.10
“ Sulphocyanide	....	....	....	2.95
“ Nitrate	....	....	....	.09
Ammonium Sesqui-carbonate	....	....	....	1.78
Sulphur	....	....	....	14.11
Charcoal	....	....	....	2.02
				<hr/>
				100.00

“ Composition by weight of the products of combustion of one gramme of fired gunpowder” :—‡

“ Proportion by weight of gaseous products,”

Carbonic Anhydride	....	....	....	.2279
“ Monoxide	....	....	....	.1522
Nitrogen	....	....	....	.0858
Sulphydric Acid (H_2S)	....	....	....	.0389
Marsh Gas (Methane)	....	....	....	.0070
Hydrogen	....	....	....	.0017
				<hr/>
				.5135

* “Philosophical Transactions,” Vol. 171, p. 278.

† Ibid, p. 278.

‡ Ibid, p. 279.

"Proportion by weight of the solid residue,"

Potassium Carbonate ....	....	....	1945
," Sulphate ....	....	....	.0028
," Monosulphide ....	....	....	.1745
," Sulphocyanate ....	....	....	.0139
," Nitrate ....	....	....	.0004
Ammonium Sesqui-carbonate	....	....	.0084
Sulphur ....	....	....	.0664
Carbon ....	....	....	.0095
			<hr/>
			.4704
			<hr/>

This solid residue was observed to be in a fluid state shortly after the explosion, and occupied an appreciable time in solidifying. The observation of this condition is expressed in these words:—"In "Experiment 77, the cylinder being perfectly full of pebble powder "and fired, was placed at an angle of 45° one minute after the "explosion, and altered every 15 seconds. It was found that at 60 "and 75 seconds after explosion, the deposit was perfectly fluid, the "evidence of each motion of the cylinder being given by a wave of "the deposit. At 90 seconds it was rather viscid, at 105 seconds the "deposit hardly moved."*

The temperature of the explosion was first sought upon the basis of the mean specific heat of the products of combustion, which for rifle grain and pebble powder gave 3812° C.† It was, however, obtained by exposing Platinum, whose temperature of fusion was known, to the action of the exploded powder, with the result that the temperature of explosion was determined to be 2231° C.‡ The later experiments fixed the temperature for mining powder at 2896° C, upon the basis of the mean specific heat of the products of combus-

* "Philosophical Transactions," Vol. 165, p. 94.

† Ibid p. 101.

‡ Ibid pp. 105, 106.

tion,* and it was added: "The temperature named in our first "memoir, viz., 2200°C , is not far removed from the truth for the "principal powders we were then experimenting."† "The data at "our disposal is not sufficient to enable us to determine the tempera- "ture of mining powder with the same accuracy, but it is probable that 2000°C and 1800°C may be assigned as the true limits."‡

The pressure developed by the explosion of one gramme of mining powder was found to be 44 tons per square inch, equal to 6,706 atmospheres.§

The time occupied in burning a charge of rifle large grain is given approximately at .00128 second, and of pebble at .0052 second.¶

In the shot hole of a mine, the gunpowder is not only absolutely closed in, but is also compressed and sealed in by the stemming. Its volume is therefore unalterably fixed until the combustion has proceeded sufficiently to evolve gas and accumulate a pressure adequate to expel the stemming or rupture the rock. In these conditions, the temperature of explosion in a mining gunpowder shot is probably higher than that deduced from the experiments under notice. The pressure developed in the ignition of pebble powder was found to be 42 tons per square inch, and the temperature of its explosive combustion 2231°C . The mining powder, however, gave a pressure of 44 tons per square inch. If one gramme of pebble powder be fired in a closed vessel and produce a pressure of 42 tons per square inch; and one gramme of mining powder be fired under the same conditions and develop a pressure of 44 tons per square inch, the unequal pressures represent inequality in the expansion of their products, brought about by

* "Philosophical Transactions, Vol. 171, p. 229. † P. 231. ‡ P. 232. § P. 231. ¶ Vol. 165, p. 98.

difference in their temperatures. The volume of gaseous products of mining and pebble powders differed in the experiments, but the conditions in the mine are being considered here.

One gramme of dry mining powder generated 360·3 cubic centimetres of permanent gas at 0°C and 760 millims. barometric pressure,* and evolved 516·8 gramme units of heat.†

The conclusions of the foregoing experimental researches were :

- (a) The temperature of the explosion of gunpowder is about 2231°C.
- (b) The time consumed in combustion is .0052 second for pebble powder.
- (c) The products of explosive combustion of mining powder are .5135 gaseous, .4704 solid, and .0161 water vapour.
- (d) The gaseous products contain 2·73% of firedamp, and 5·24% of free hydrogen. The solid products contain 14·11% of sulphur.
- (e) The solid products are in a state of fusion, and occupy 1½ minutes in solidifying.
- (f) One gramme of powder generates 360·3 cubic centimetres of gas, and evolves 516·8 gramme units of heat.
- (g) At 2231°C the temperature produced by the explosion of mining powder, the gases produced, which would occupy a volume of 360·3 cubic centimetres at 0°C, would expand, exerting a pressure of 6,706 atmospheres, or 44 tons per square inch, in the space available for the gas.

The quantity of heat generated in the explosive combustion of the gunpowder in No. 2 shot, now becomes a simple computation. The shot contained 12½ ounces or 354·375 grammes of gunpowder. The mean

* "Philosophical Transactions," Vol. 171, p. 229.

† P. 226.

specific heat of the products of combustion of a gramme of mining powder was determined by Sir Frederick Abel and Captain Noble to be $\cdot 17846^*$ (unity being the quantity of heat required to raise an equal mass of water from 0° C to 1° C). The combustion of one gramme of mining powder evolved $516\cdot8$ gramme units of heat, and dividing this quantity by the heat necessary to raise the products of combustion through 1° C , that is to say $\frac{516\cdot8}{17846}$, the temperature of the products is found to be 2896° C .

The co-efficient of the expansion of gases is $\cdot 00366$ or $\frac{1}{273}$ of their volume at 0° C for each centigrade degree, therefore at the temperature of 2896° C the gases would be expanded by $\frac{2896}{273}$ or $10\cdot6$ their volume at 0° C , and each volume of gas at 0° C would become $1 + 10\cdot6 =$ to $11\cdot6$ volumes at the temperature of the explosion.

It has been already observed that one gramme of mining powder generates $360\cdot3$ cubic centimetres of gas at 0° C and 760 millims. barometric pressure, consequently $360\cdot3 \times 11\cdot6$ equal to $4179\cdot48$ cubic centimetres would be the volume at this temperature and pressure, of the gases generated by one gramme of gunpowder at the moment of explosion. The product of $354\cdot375$ grammes by $4179\cdot48$ cubic centimetres represents $1,481,103$ cubic centimetres or $52\frac{1}{2}$ cubic feet of gases generated by the charge in No. 2 shot.

The combustion of one gramme of mining powder produces a solid residue equal to $\cdot 4704$ by weight of the products, therefore the charge in No. 2 shot would yield $354\cdot375 \times \cdot 4704$ or $166\cdot7$ grammes of solid products which at the moment of explosion were in a molten state, and contained both their sensible heat, and heat of fusion. The portion of the heat generated by the explosion which is at the command of the solid products, is employed in producing fusion (which is latent so long

* Philosophical Transactions, Vol. clxxi., p. 228.

as the products are liquid) and in raising them to the common temperature. These solid products therefore cannot fail to have an important effect on any carbonaceous matter upon which they may be projected.

The quantity of heat generated by the explosive combustion of the charge of gunpowder in No. 2 shot was 354.375×516.8 or 183,141 units of heat; the unit of heat being the quantity of heat necessary to raise one gramme of cold water through 1° C.

In an ordinary blasting operation, when the gunpowder is fully expended in breaking ground, as in No. 1 shot, the solid residue is evidently vaporised by the high temperature and scattered in a state of fine division; a considerable portion of the chief potassium compounds forming smoke. If the hole be overcharged with gunpowder, as in No. 2 shot, the stemming is expelled and the stone is ruptured through a limited area, when combustion has proceeded far enough to accumulate the necessary pressure. The condition of the explosive charge at the moment of ignition is one of partially completed combustion, and the first movement of the stemming or the strata allows expansion, in which the combustion is perfected. The rupturing force developed proved unequal to dislodge the stone bridge as intended; it therefore broke through lines of less resistance, and produced the form of rupture shown in Plate VI., Figs. 29 and 31. The products of combustion consequently escaped through the small area of rupture, at their high temperature to produce effects upon the coal-dust, which will be subsequently dealt with. It would be a misconception to suppose that the term "A blown-out shot" means in this case that the ignited gunpowder was expelled through the mouth of the hole in a cylindrical form, as a charge of small shot is projected from a gun. There was no doubt more projectile force down the axis of

the hole than elsewhere, due to the joint at the back arresting the forward ripping; but there was propulsive force through the area of rupture.

In No. 2 shot the front line of rupture was through the axis of the hole, and extended about 9 inches on either side, then feathered out on the south side, but on the north broke down abruptly through the stone forming a face with a sharp declivity, whose extension intersected the side wall of the Incline. The joint at the back of the hole formed a descending and receding face. (Plate VI., Fig. 31.) The lines in which the stone broke from its bed forming the cavity produced in the roof, presented a series of irregular planes radiating from the shot hole; and the products of the exploded gunpowder escaped down these planes into the coal-dust in fan-like sheets. In front of the hole they formed a descending plane corresponding with its declivity, and struck the dust on the bank and the floor of the Incline. On the north side they had a short cut down the face of the stone direct on to the dust of the bank. At the back they would rush down the face of the joint on to the dust of the floor. The action on the south side appears to have been slower, the ripping extended further and thinned out; the bulk of the products therefore escaped on the other sides.

The position of the hole and the form of the ground broken suggest that there was a conservation of energy in the combustion of the explosive, and it is probable that the gaseous products, in the high temperature present, differed in some measure from those obtained in the experiments. Experiments (which will be referred to in a succeeding page) have proved that fire-damp decomposes, yielding free hydrogen at a much lower temperature than that of exploded gunpowder, and probably sulphuretted hydrogen is equally

unstable in the same circumstances. It is more than likely that several of the gaseous bodies observed in the experiments with fired gunpowder, were decomposed here if in fact they had an appreciable existence, and that hydrogen ultimately existed in a free state in the products.

The dust in the Incline in the vicinity of the shot, presented unmistakable evidence that it had been exposed to a high temperature. The face of the north bank (Plate VI., Fig. 32) was covered with cindered or coked coal-dust from the timber prop H to a point above No. 2 shot, and it was hollowed out above the prop H where the products of the shot would strike it. The action at this hollow was more energetic than elsewhere. Where the bank reached the side of the Incline some pieces of the strata had loosened down and rested on the dust (Fig. 32). The coal-dust in an intumescent condition, had been driven into the interstices of these stones, and could only be extracted by separating them, when it was found to be a carbonised residue, its gases having been distilled out.

The exposed portion of the prop H (Figs. 27 and 31) measured 3 feet from the surface of the bank to the roof. The first 12 inches above the dust, and facing No. 2 shot, was covered with a matted mass of coked and cindered dust, and the end of the prop I adjoining was in a like condition. The upper 2 feet of prop H towards No. 2 shot had only traces of coked dust, and its opposite side facing down the Incline had none.

The coked dust on the surface of the north bank was only observed about three months after the explosion, when the plottings of the angles and declivities of the shot holes, suggested its examination. At that time there had been many inspections of the workings, and the travelling over the floor had removed any possibility of

discovering the coked dust that no doubt existed there immediately after the explosion. The prop J (Plate VI., Fig. 28) on the south side of the Incline, had coked dust on its face towards No. 2 shot for 12 inches above the floor, but nothing above nor on the opposite side. A block of wood K beside it on the floor was also coated with cindered dust. There was an iron plate (Plate VI., Figs. 27 and 28) 4 feet by 2 feet, standing upon its end against the deep side in No. 2 Refuge hole. Its face towards the shot was covered with fine dust containing swollen and crusted particles. The prop L in the Refuge hole had coked dust on its upper end towards the deep side, and the prop M opposite the Refuge hole, on the north side of the Incline, had coked dust in a similar position, both on the contrary side to the shot. These coked residues on the props and timber J and K show that the dust on the floor of the Incline between them had been subjected to distillation in the same manner as that on the north bank, and these chemical activities were continuous from No. 2 shot to the iron plate in No. 2 Refuge hole, a distance of 14 yards 1 foot.

The next point to observe was that the deceased men's candlesticks were found fixed in the face of No. 4 Refuge hole, 35 yards from the shot, showing that they had retreated here for safety when they had ignited the "Match" to fire the shot. The bodies were 19 yards lower down the Incline, but the positions of their burns showed that they had received them while in the Refuge hole, and that they had travelled down the Incline subsequently. The evidence is complete that the heated products of the gunpowder from No. 2 shot disengaged the gases contained in the coal-dust upon the bank and floor of the Incline for a distance of over 14 yards in this direction, producing a gaseous body of high temperature, and that such a gaseous body passed No. 4 Refuge hole 35 yards from the shot. Its presence at

that Refuge hole shows that the gas-generating activities continued to that point, though there are no coked residues to mark their progress beyond No. 2 Refuge hole. (It will be well to observe here that these coked residues were only deposited on the timber when certain forces were exerted which will be referred to again.) The suggested point where this gaseous body was ignited in this direction is 140 yards from the shot. The coal dust was continuous between these points: chemical activities were in progress for the first 35 yards, and there is no evidence of their arrest, nor any apparent reason why their continuity should be broken. In these circumstances they could only be stopped by the temperature falling below the distilling point; but, inasmuch as there was adequate heat to determine its ignition at the 140 yards, and that that heat exceeds the temperature at which distillation proceeds, it will be clear that the chemical activities were uninterrupted. It is, therefore, obvious that a gaseous body was produced between No. 2 shot and the centre of the initial gaseous explosion down the Incline.

Proceeding from the shot up the Incline, the feet of the props on the north side for 50 yards had coked dust deposited upon them, on their sheltered sides, contrary to the advance of the gas generating activities: showing the production of a gaseous body in this direction also. The suggested point of the gaseous explosion on this side is 136 yards from the shot. The gas generating action proceeded for the first 50 yards by the evidence of the coked deposits, and the observations made as to the continuity of the action down the Incline apply here equally. The coal-dust was continuous throughout: there was no apparent reason for the suspension of the chemical activities; and there was sufficient heat at the end of the 136 yards to determine the ignition of the gaseous body, which shows the temperature

there exceeded the distilling point. It is also obvious that a gaseous body was produced between No. 2 shot and the initial gaseous explosion up the Incline. The gulf between the No. 2 shot and the initial gaseous explosions on either side, is now seen to be filled with physical and chemical activities adequate to produce the phenomena of those explosions. Starting with the products of the exploded gunpowder in No. 2 shot, processes were set up in the coal-dust, which continued for 136 yards and 140 yards respectively in opposite directions, and produced distinct and definite gaseous explosions at those points.

Before proceeding to enquire the character of the explosive gaseous body produced, the positions of the coked residues upon the timber may be considered. The deposits on the bottom ends of the opposing faces of the timbers H and J are readily accounted for, as they were exposed to the projectile force of the shot. Those on the props L and M in the No. 2 Refuge hole and on the opposite side of the Incline respectively, were probably produced by the heated gases in the chemical activities, and subject to the propulsive force of the shot; striking the iron plate, between the props, spreading in both directions, rushing up to the roof, and impinging upon the timber, depositing the intumescent coal-dust they had carried up from the floor. Coming to the residues on the lower sheltered ends of the timber between the shot and the top of the Incline, Plate 3, Figs. 5 and 6, it would appear singular that they should be found there, and not on the opposing faces as on the props between the shot and No. 2 Refuge hole. It will be remembered that the direct projectile force of the shot was towards that Refuge hole, and greatly exceeded the propulsive force up the Incline. It is clear that in the physical and chemical activities that proceeded

up the Incline, the carbonised residues were not driven against the opposing faces of the timber, but were deposited in the rear of these processes. These activities would leave the atmosphere in their rear in an attenuated condition, and when No. 1 gaseous explosion occurred (which was unquestionably the first gaseous ignition) there would be an instantaneous rush into this attenuated atmosphere, driving the intumescent dust that had not subsided, against the then opposing faces of the timber. This phenomena is important as showing, that where the processes in the coal-dust are not exposed to the immediate projectile contact of the products of the exploded powder, there is no deposit of coked residues on the objects passed, and that the activities were in active progress where no such deposits existed. It is also to be observed that the effects of this projectile contact were lost between 14 and 15 yards from the shot, and coked deposits ceased, though the physical and chemical activities continued. It must be remarked in connection with these depositions of coked dust, that excepting those produced by the projectile contact referred to, they only arose after an explosive ignition of the gaseous mixture, and not during its production, and were consequently due to forces set up in the atmosphere by the explosions.

The gases that produced the explosive phenomena were significant in character, inasmuch as upon their ignition they reinstated the activities by which they were themselves produced; and propagated the explosions. The first step in elucidating their constitution is to consider the nature of the coal from which they were produced.

The coal of the seams in which the explosions occurred is used for gas making and house purposes; and is represented by the following analysis :

SMALL COAL.

Specific gravity	....	....	1.278.	Water being 1.00
Fixed products or coke	....	66.45	per cent.	
Volatile products	....	33.55	"	
Sulphur in the coal	....	1.41	"	
Ash	....	10.70	"	

The quantity of purified gas per ton at 30 in. Bar. and 60 Fahr. was 11,134 cubic feet.

Sulphuretted Hydrogen in the crude gas	....	·58	per cent.
Carbonic Acid	....	....	3.16
Hydrocarbons condensable by Bromine in the purified gas	....	....	5.84
Carbonic Oxide in the purified gas	....	5.57	"

The illuminating power of the gas when burned in "The London Argand" at a rate of 5 cubic feet per hour was equal to the light of 18.19 Spermaceti candles, each consuming 120 grains per hour.

Value of one ton of the coal in lbs. of Sperm 694

The heating power of the coal is 12.9, or 1 lb. of this coal by its perfect combustion will convert 12.9 lbs. of boiling water into steam.

Analysed by

ALEXANDER H. FIDDES, Esq.,

Bristol, 18th August, 1887.

The points of the analysis are the large volume of gas yielded, and the rich hydrocarbons represented in its high illuminating power. The coal-dust was therefore a favourable material for yielding a gaseous mixture, and contained a good proportion of the higher hydrocarbons in the ascending scale of explosive combustion. The deposits of carbonised residues in the incline, show that the volatile products had been more or less extracted from the dust; but, so far, there has been no evidence as to their ultimate composition.

It has been observed that the coked residues were upon the surface of the accumulated dust upon the bank, or the bottom ends of the timber props, showing that the distillation had proceeded in the dust upon the floor. The heated products of the gunpowder in striking the floor with projectile force would cause the dust to rise; and in the process of distillation the particles would swell and ascend with the gases yielded, and be deposited on any object that presented a surface favourable for their detention, or fall back upon the floor when their gas had been extracted. Taking the heights of the deposits upon the timber, it appears that there was a stratum of dust from 12 inches to 15 inches thick upon the floor of the incline, out of which the gases rose filling the intervening space to the roof. The gaseous products of this dust would depend upon the temperature at which they were generated. If the evolved gases corresponded with the first products yielded by the coal in a gas retort, then the temperatures of the action in the incline would approximate to that in the retort. The gas engineer seals his coal in the retorts and subjects it at first to a temperature of about 334°C , increasing it gradually to a much higher point, but below $1,000^{\circ}\text{C}$. At the end of the process a gaseous mixture is produced which is represented by the gas in public consumption. This mixture has been exhaustively investigated, and is fairly indicated in the following analyses.

Analyses of the products of the distillation of bituminous coal.*

			London Gas. Frankland.		Heidelberg. Landolt.
			<i>a</i>	<i>b</i>	
Hydrogen ....	....	....	50.05	51.24	44.00
Marsh Gas (Methane) ....	....	....	32.87	35.28	38.40
Carbon Monoxide ....	....	....	12.89	7.40	5.73

* Roscoe's and Scholemmer's Chemistry, p. 693.

	London Gas. Frankland.		Heidelberg. Landolt.
	<i>a</i>	<i>b</i>	
Olefines	3.87	3.56	7.27
Nitrogen	—	2.24	—
Carbon Dioxide .... .... ....	.32	.28	4.23
Oxygen	—	—	.37
	100.00	100.00	100.00

These results were obtained by gradual distillation extending over six hours. In the investigation of the effects of temperature in gas distillation, the products issuing from the retorts at different periods of the process, have been examined, and go to show that when the coal is first subjected to heat the predominating product is methane, with some olefines and acetylenes. The temperature of this stage commences at about 334° C; and, as it increases, the yield of hydrocarbons decreases, and hydrogen is largely obtained. The following table by Dr. Henry illustrates this action.*

	Specific gravity.	Hydrogen.	Marsh Gas.	Olefines and Acetylenes.	Carbon Monoxide.	Nitrogen.
1st hour ....	.633	8.3	70.8	12.3	5.8	2.7
5th , , ....	.500	21.3	56.0	7.0	11.0.	4.7
10th , , ....	.345	60.0	20.0	.0	10.0	10.0

The ordinary process of gas distillation, therefore, gives some indication of the character of the gaseous mixture that would be yielded by the coal-dust in the incline at corresponding temperatures.

Returning to the mine with this knowledge, but remembering that the processes there were but momentary as compared with those just considered, it is difficult at this stage of the enquiry to find any indication that the gaseous mixture formed there corresponded with that yielded in the first hour in gas retort distillation. The results given in Dr. Henry's table, showing that the products are as the temperatures,

* Muspratt's Chemistry, 2 Ed., p. 999.

would appear to apply in a comparatively instantaneous as well as a gradual process; and if the temperature in the incline equalled the maximum in the retort the products would presumably be alike. Such a conclusion would make the gaseous mixture under consideration practically correspond with Professor Frankland's analyses, which indicate the presence of considerable quantities of hydrocarbons. A mixture of this character would scarcely leave any direct evidence of its presence in the incline, until it had undergone combustion, and it will be useful at this stage to enquire into the temperatures which determine the combustion of the gases yielded by coal.

Experiments have recently been conducted by Professor Victor Meyer and Herr A. Munich, at Heidelberg University, to ascertain the behaviour, and the temperature of ignition of hydrogen and some hydrocarbon gases. The results of their investigations have been translated, and the substance of them is published in *Nature* of December 7th, 1893, from which the following particulars are taken.

Mixtures of hydrogen and oxygen were ignited between 612° and 686° C., and it was found to be immaterial whether the mixture was dry or moist: if dry, a small amount of silent combustion rendered it moist before the explosion occurred.

Methane CH₄ and oxygen exploded as a rule between 656° and 678° C.: occasionally quiet and complete combustion occurred, but the other hydrocarbons never failed to yield an explosion.

Ethane C₂H₆ detonated with oxygen in three experiments at 622°, 605°, and 622° C.

Propane C₃H₈ exploded with five times its volume of oxygen in three determinations at 548°, 545°, and 548° C.

Iso-butane C₄H₁₀ detonated with six-and-a-half times its volume of oxygen at 549°, 550°, and 545° C.

In the Olefine series, Ethylene C_2H_4 and oxygen exploded at 577° , 590° , and 577° C.

Propylene C_3H_6 exploded with four-and-a-half times its volume of oxygen at 497° , 511° , and 499° C.

Iso-butylene C_4H_8 exploded at 546° , 548° , and 537° C.

In the Acetylene series, Acetylene exploded with oxygen with exceptional violence at 509° , 515° , and 510° C., in three consecutive experiments.

The mean temperatures of ignition were: Methane 667° C., Ethane 616° C., Propane 547° C., Isobutane 548° C., Ethylene, 580° C., Propylene 504° C., Iso-butylene 543° C., Acetylene 511° C.

Methane, with the three succeeding members of the Paraffin series, and another corresponding very nearly with Pentane C_5H_{12} , were discovered in Ryhope coal by Mr. W. McConnell, junr., A.Sc.* and the above-named members of the Olefiant and Acetylene Series are found in the products distilled from coal.

Bringing the results of the Heidelberg experiments to the examination of a gaseous body like that produced in the retorts, at something below 1000° C., it is difficult to understand how it would escape more or less combustion in the presence of air, seeing that the temperature exceeded the ignition points of all the constituent gases. The products of the combustion of such a gaseous body are definite, and could not escape detection; but they were absent in the path of the explosion. It would appear therefore that the gaseous body produced from the coal-dust in the Incline differed from that yielded in the gas retort, and as the temperature of the exploded gunpowder is much higher than that of the retort, the chemical actions that proceed in

* Report of an Investigation on the Gases enclosed in Coal and Coal-Dust.

hydrocarbon gases when subjected to temperatures above 1000° C., must be considered.

The effect of high temperatures upon methane, ethane, and ethylene has been recently investigated by Professor Vivian B. Lewes, in a series of experiments which have been given in a Paper to the Royal Society, and published in the *Chemical News* of February 23rd, March 2nd, 9th, and 16th, 1894. The stabilities of these gases at high temperatures were investigated, and it was found that they were all decomposed: the carbon being deposited and free hydrogen produced when the highest temperatures were reached. The results of the experiments with methane were as follows:—*

“TABLE IV.—The action of heat upon Flowing Methane.”

Percentage of methane in original

gas	99.2	99.2	99.2	99.2
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Temperature of the gas in the

decomposing tube	1000° C.	1200° C.	1300° C.	1500° C.
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Analysis of the gas after heating:

Unsaturated hydrocarbons	trace	0.07	0.39	1.20
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Containing acetylene	trace	0.07	0.39	0.963
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Saturated hydrocarbons	97.65	90.00	88.52	19.22
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Hydrogen	1.55	8.53	10.37	78.66
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Carbon deposited and oil formed

in grms. per 100 c.c. of gas:

Carbon	0.0	0.0	trace	0.015
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Oil	0.023	0.0025	0.0005	0.0
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At 1000° C. decomposition commenced and increased slowly up to 1300° C., but at 1500° C. the gas was breaking up, yielding at that stage 78.66% of free hydrogen. Professor Lewes states: “It probably decomposes at first into acetylene and hydrogen according to the equation $2 \text{CH}_4 = \text{C}_2\text{H}_2 + 3 \text{H}_2$, and then the acetylene either

* *Chemical News*, March 9, 1894, p. 111.

polymerises or decomposes to carbon and hydrogen according to the temperature.”*

The effects upon Ethane were more pronounced.

“ TABLE III.—The Action of Heat upon Flowing Ethane,”†

Percentage of Ethane in original

gas	96.38	96.38	96.38	96.38
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Temperature of gas in the de-

composing tube	900° C.	1000° C.	1200° C.	1500° C.
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Analysis of the gas after heating :

Unsaturated hydrocarbons	31.00	28.42	11.58	1.69
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Containing acetylene	...	trace	0.30	1.80	0.91
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Saturated hydrocarbons :—

Paraffin	12.82	8.34	3.88	0.00
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Methane	12.01	12.73	21.86	20.62
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Hydrogen	40.64	46.78	57.45	73.35
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Carbon deposited and oil formed

in grammes per 100 c.c. of

gas :—

Carbon	0.0	0.0	0.0126	0.0314
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Oil	0.0	trace	trace	0.0
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Professor Lewes observes: “ These results show that even below 900° C., ethane decomposes with liberation of hydrogen, and formation of unsaturated hydrocarbons which on examination prove to consist of ethylene with small quantities of acetylene, rise of temperature completing this decomposition, and also causing the ethylene to decompose.”

The action of elevated temperatures upon ethylene is described as follows: “ No change takes place until a temperature of 800° C. is reached, when traces of acetylene are observed; between 800° C. and 900° C. the acetylene increases in quantity, and large quantities

* *Chemical News*, March 9, 1894.

† *Chemical News*, March 2, 1894.

" of methane are generated accompanied by liquid products. This action increases until just below 1200° C., when hydrogen begins to appear amongst the products of decomposition, whilst the moment the liberation of hydrogen commences, carbon is deposited and the formation of oil decreases until close upon 1500° C., when the decomposition of the ethylene is practically complete, and the products of decomposition are mainly hydrogen, with some undecomposed methane and a copious deposit of carbon."* These results are tabulated thus:—

" TABLE I.—The Action of Heat on Flowing Ethylene,"†

Percentage of ethylene in

original gas	96.78	94.8	94.8	98.91	98.91
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Temperature of gas in de-

composing tube	800° C.	900° C.	1000° C.	1200° C.	1500° C.
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Analysis of gas after heat-

ing, per cent:—

Unsaturated hydrocar-

bons	96.46	34.77	18.02	10.54	0.43
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Containing acetylene	trace	0.82	0.60	3.60	0.00
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Saturated hydrocarbons	0.00	59.73	76.48	55.26	27.80
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Hydrogen	0.00	0.00	0.00	25.11	62.68
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Carbon deposited and oil

formed in grammes

per 100 c.c.:—

Carbon	0.00	0.00	0.00	0.0273	large quantity
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Oil	0.00	0.0024	0.0048	0.0038	0.00
----------	------	------	--------	--------	--------	------

Change of volume none decrease decrease increase large increase.

Professor Lewes has shown that Methane is the most stable of the hydrocarbons, and if the temperature at which it undergoes decomposition be reached, the separate existence of the other hydrocarbons

obtained from coal by distillation is precluded, and the ultimate gas must be hydrogen.

If these investigations be applied to the chemical activities in the Incline, and it be remembered that the temperature of the exploded gunpowder largely exceeded the highest point touched in Professor Lewes's experiments, the character of the gaseous body produced from the coal-dust becomes revealed.

What gaseous bodies were first produced when the coal-dust was subjected to the temperature of the products of the gunpowder, remain to be determined. Assuming they contained methane, and the hydrocarbons evolved from coal, the temperature was sufficiently high in the immediate vicinity of the shot to effect dissociation to carbon and hydrogen at the moment of their liberation. The chemical actions that arose were undoubtedly complex in character, but there can be no question that hydrocarbons would be decomposed, the carbon being deposited, and a body of free hydrogen produced. Whether the decompositions were perfect, and hydrogen was the exclusive product, depends upon the temperatures in the reactions that occurred and the quantity of heat available; but Professor Lewes has shown that acetylene is a first product in the decomposition of methane, ethane, and ethylene, and he suggests that the nascent acetylene liberated from ethylene by the action of heat is practically condensed instantaneously to form benzene C_6H_6 , which, he adds, would be dissociated to carbon and hydrogen if the temperature were sufficiently high. In these secondary actions some hydrocarbons would remain undecomposed, but probabilities point to hydrogen as a permanent product in the ultimate gaseous body evolved from the coal-dust.

The aspect presented in the Incline by chemical activities of the

character under discussion, would presumably be a stratum of dust in an intumescent condition, undergoing distillation: its upper surface resembling the face of troubled water, and merging irregularly into the gases yielded. This body of gases would be undergoing partial decomposition yielding hydrogen as a product, and depositing carbon. These processes are the evidence that the evolved hydrogen was at a very high temperature, and, as it is an elementary gas, it could leave no impressions on passing any objects whereby its existence could be proved, but it would yield indications of its exalted temperature upon any carbonaceous matter that it came in contact with, and its oxidation would be accompanied with detonating violence. Again, the possible explosive gases here would be limited to the hydrocarbons and hydrogen, and in the products of their combustion they would be respectively indicated. In the decompositions of hydrocarbons the carbon would be deposited in an exceedingly fine state of division, very difficult to discover in a dark and dusty Incline, except it became attached to the side walls and timber. The stratum of coal-dust under distillation would leave evidences in coked residues on the floor and upon surfaces favourable to retain them if contact were produced. The deposits upon the floor would, however, be subsequently covered in many places with that film of brown sooty dust which is the last to subside after an explosive ignition.

The indications of the distilling process have been already observed in the coked dust upon the surface of the bank, and on the feet of the timber in the vicinity of the shot, and they are sufficiently definite to identify this stage of the activities.

A copious and disseminated deposit of carbon must have resulted from the decomposition of the distilled gases; but it would be useless to seek for it in the dust upon the floor, where its exceeding fineness

would baffle its discovery. There are, however, depositions of carbon on the surface planes of the strata forming the walls of the Incline, and upon standing timber, in impalpable powder and filament form. These filaments are deposited like gossamer, striated in short down-like threads, and prevail to an ample extent to prove that chemical activities had been in progress, of which one result was the dissociation and copious deposit of carbon. The impalpable powder is deposited on faces of strata, giving them a faintly stained appearance, and completing the traces left of the second stage of the processes.

The first evidence of the high temperature of the evolved hydrogen, occurs in No. 2 Refuge hole, where there was a calico bag containing the food of one of the deceased men, freely suspended by ordinary cotton tape from a timber collar in the roof, 18 inches back from the face of the wall of the Incline—Plate VI, Figs. 27 and 28—and its bottom end was about 4 feet above the floor. This bag was found still hanging after the explosion, but the texture of the material was changed; the fibrous structure and tensile strength were destroyed; and the contents had broken through the bottom and fallen to the ground. The fabric of the bag was not consumed, but the inflammable elements were distilled out of the cotton, as the gases were distilled out of the coal-dust, leaving in both cases a carbonised residue. The condition of the bag showed that it had not been exposed to the action of flame, but that it had been subjected to the distilling action of an intensely heated gas, so that its structure was left intact, hanging by its cotton tape. It also shows that the gases yielded by the material were not ignited there, and that there was no explosive combustion.

The next observation is in the burns upon the deceased men. It will be remembered that they were in No. 4 Refuge hole when the

shot fired, and that they had attempted to escape to the shaft, so that their bodies were found 19 yards below the Refuge hole. The concussion of the shot undoubtedly extinguished their lights, and the phenomena produced by the products of the exploded gunpowder in the coal-dust must have been of a terrifying character. The alarm of the deceased men when the heated gases rushed upon them, is reflected in the fact that, though their candlesticks were at their fingers' end, they did not seize them to relight the candles, but fled upon a journey of 2,400 yards through dark and tortuous roads without any light to guide them, which was at best but a forlorn hope. They worked in the manner usual in the district, with only trousers and boots on, the upper part of their bodies being exposed. The nature of the burns they received is described by Dr. Frank Woods in his Medical Report, which is given below, as it affords some evidence of the heated atmosphere in the Incline at this point. This Report says:—“The man (Hawkins) was burnt on both arms, front and back of chest, the burns being of the 3rd degree, viz., formation of blisters which had discharged their contents, and the true skin was also burned beneath. Owing, I suppose, to his having his trousers on, the burns did not extend past his navel, the head was also burnt, particularly at back of neck, both cheeks and forehead, and the hair was singed all round back of neck. The burns if anything were more numerous on his right side. I found no fracture of bones or wounds, and to the best of my knowledge he was burnt before and not after death. I form this opinion from the appearance of the burns, which would have had quite a different look if he had been killed and then burnt.”

“ As to the boy (Tarrant), he was burnt in the same manner and degree, but very strikingly upon the right side and very slightly on

“ his back, and that only on his right side. The only part burnt of
“ the left side of body was his left arm ; in other respects he was
“ burnt exactly like the man, and I have come to the same conclusion
“ that he also was burnt before death.

“ Now, as to exact cause of death, it is rather difficult to say ;
“ but there is no doubt that the largeness of surface burnt on both
“ bodies was quite sufficient to cause death from shock in both cases,
“ and as far as external appearances, I could not detect that suffoca-
“ tion had been the cause.”

The positions of the burns show that the deceased were not escaping down the Incline, but were in the No. 4 Refuge hole, when they were burned. The Refuge hole was on the left side in descending the Incline (Plate VI., Figs. 27 and 28), and the natural positions of the deceased would leave their right sides towards the Incline. The extinction of the lights by the concussion of the shot was a common experience, and would not occasion any alarm. When the deceased men sat down in the Refuge hole, with their backs against the sheltered side towards the shot, as is usually done, they knew they had repeated only what had been done thousands of times in the mine : they had fired a shot. The only possible danger they believed to be the projectile force of the dislodged débris, and from that they were safe. When the shot fired, Hawkins as an experienced man would know by the sound that it had not done much execution ; but the possibility of a distillation of the coal-dust, and the ignition of the evolved gases, would not enter his mind. He would wait a few moments after the report, for the fragments projected into the air to fall, and for the smoke to clear, insensible of the danger that had arisen ; and the hot gases would rush upon him and his comrade before the consciousness of peril arose. In the Refuge hole they were sheltered from the direct

rush of the hot gases, which on reaching that point would expand in upon them, and their right sides being exposed were more severely burned. Hawkins was evidently on the outside, and Tarrant on the inside of the hole, with his left side protected by contact with the face of the strata ; the former would therefore be enveloped with the gases, but only the right side of the latter could be attacked, hence the limitation of the burns on that side of his body. They were, however, burnt in exactly the same manner, and over large surfaces, especially about their heads and necks, which were most easily enveloped.

The character of the burns upon the deceased men indicated that they had been produced by gases at an exalted temperature, similar to those shown to have been present at No. 2 Refuge hole, and that they had not been exposed to flame. Flame of sufficient persistency to effect burns of such a nature, must have consumed all the hair upon their heads, as in an ignition of fire-damp ; especially as the burns were worst upon those portions of the bodies and the heat most intense at those points. The hair was simply singed round the back of their necks, and it is clear that the gases in the upper part of the sectional area of the Incline were at a high temperature, like those to which the food-bag was exposed.

There are no further distinct evidences of the temperature of these gases between No. 4 Refuge Hole and the first fall below the centre wheel, due probably to the fact that there were no other objects calculated to retain impressions ; but that they did possess great heat on reaching the wheel is placed beyond question in the fact that they had there a residual or supplementary source of heat, adequate to determine their explosive ignition, as already observed.

Carbon dioxide could not be detected in the products of the explosive combustion, consequently the carbon of the hydrocarbons

present could not have undergone oxidation ; the explosion must therefore have been due to the hydrogen, which was the only other constituent of the gases evolved by the coal-dust to produce the phenomena.

The product of the oxidation of hydrogen is steam at a very high temperature, which undergoes liquefaction upon the surrender of its heat. This steam would be diffused in the atmosphere at the seat of the explosion, and in its condensed condition of water it could not be discovered, excepting it was subjected to instantaneous condensation upon cold surfaces, that would retain some impression of its contact. The frame which sustains the centre wheel in the Incline is built up of large timber with sawn faces. One beam is placed across the Incline from side to side near the roof, at the upper side of the wheel. On the face of this beam towards the wheel, and looking down the Incline, there were numerous stains of a dark colour, like that produced by dirty water, and of an irregular elliptical form. They appeared as if they had been produced by water being driven against some object near the wheel on the north side of the Incline, and that drops had been deflected from the object, striking the face of the beam at a tangent with projectile force. In the Author's inspections, this phenomenon was examined several times ; it appeared that it was not there before the explosion. The Incline at the place was perfectly dry ; water was not required and never taken there ; the only liquid present was the oil or grease used to lubricate the bearings of the gudgeon of the wheel, and no explanation could be found. The oxidation of the hydrogen gas in the explosion below the wheel, appears to the Author to suggest an interpretation of the phenomenon. The volume of heated steam produced in that explosion would be propelled in both directions from the point of ignition ; that portion coming up the Incline would find room for expansion and consequent part cooling in the pass-bye, and coming in contact with the

cold metal faces of the wheel ; condensation and liquefaction would be produced, and the drops of water thus formed on the surfaces of the iron, and coloured by dirt upon it, would be deflected off, and some of them may have struck the face of the beam as observed.

This solution of the phenomenon gathers importance from the fact that all the conditions of its production were present, and that water would be the product of the oxidation of the gas, that both scientific experiments and practical evidence suggest was present, and which did undergo oxidation in the vicinity.

The remaining property of hydrogen is the detonating violence exhibited in its oxidation, the effects of which are seen in the destruction in the Incline. The evidences of the final stage of the chemical activities are now complete.

The processes that commenced in the contact of the products of the exploded gunpowder with the coal-dust have now been traced up to the production of the explosive gas, that on reaching the centre wheel on one side of the shot and the air pipe on the other, had obtained a supply of oxygen for its combustion, and brought about the initial gaseous explosions at these points.

PROPAGATION OF THE EXPLOSION.

THE initial gaseous explosions were repeated again and again, both with and against the air-currents, and the examination of this branch of the subject will be facilitated by first considering the phenomena observed by Mr. Garthwaite, Mr. Moon, and the exploring party, immediately after the disaster.

The destruction of the doors at Tom's Road, which divided the Intake and the Return airways, suspended the circulation of air in the New Branch and South-east Incline districts ; the Horse Road and Inclines were therefore filled with the gaseous mixture which existed after the explosion had taken place. The Intake air-current escaped through Tom's Road into the Return airway, receiving by suction and diffusion some of this gaseous mixture which has been described as producing a " Burning odour." Sometime after the explosion, the man who was stationed at the bottom of the downcast shaft travelled into the junction at the Horse Gug, and on passing through the double doors there, observed this odour in the return air, and he then suspected that something unusual had happened. Returning to the Intake, he proceeded towards the Pump Corner to discover what had occurred, but found the road blocked by a fall, which showed that an accident had happened. He then returned to the shaft and reported what he had discovered, and Mr. Garthwaite immediately formed an exploring party and proceeded down the shaft to rescue the men that were known to be working in the New Branch, and on the South-east Incline ; and who,

he knew, would be in jeopardy by the condition of the return air. He found the Main Intake was blocked by a fall between the Horse Gug and Tom's Road, and progress being barred in that direction, he returned to the Horse Gug, for the purpose of getting into the workings through the Return airway. At the bottom of the Horse Gug he met the four men who were engaged in the New Branch district, coming out to the shaft, because the condition of the air had led them to think that some derangement of the ventilation had occurred; and on coming out of their working places to the Pump Corner, they found the doors broken to pieces, the air-crossing collapsed, and their escape to the shaft cut off by falls in the main Intake. They then decided to try and get to the shaft through the Return airway, and were on their way hence when met by the exploring party. The two men in the South-east Incline remained unaccounted for, and the explorers pressed forward to rescue them.

Re-entering the main Intake inside of the falls they were opposed by the stagnant gases, necessitating the restoration of the air-current before they could advance further. Stoppings were put into Tom's Road and the New Branch, air-space made over the falls, and the full force of the Intake current directed into the body of stagnant gases in the Horse Road, with the result that Mr. Garthwaite reached the bodies in about eight hours after the explosion and found life extinct. He describes the gaseous mixture that filled the roads and inclines, as "Suffocating, pungent, and irritating." The effects on Mr. Moon were more pronounced, causing great difficulty in breathing. Many times Mr. Garthwaite advanced more rapidly than the fresh air, getting into the stagnant gases, and invariably experienced the sensations named; necessitating immediate retreat to the air-current. On one occasion, encouraged by his naked light burning clearly, he pressed forward in front of the current and

suffered loss of muscular power which caused him to stagger and reel, and he had to be assisted back into the fresh air, where he soon recovered sufficiently to resume the advance.

The candles of the exploring party are stated to have burned as brightly in the stagnant gases as in the fresh air; and they could only discover in which atmosphere they stood from the sensations they experienced in them.

Sooty filaments of carbon were suspended in the poisonous air from one end to the other of the roads traversed by the explosions. The floor, rails, and horizontal surfaces were covered with a film of brownish dust.

When the ventilation had been restored, the workings were inspected and tested by Mr. A. H. Stokes, H.M.'s Inspector of Mines, with his Spirit flame safety-lamp; and by Professor H. B. Dixon, one of the members of the Royal Commission inquiring into the subject of coal-dust, with the Hydrogen-flame safety-lamp; but no trace of inflammable gas was discovered.

From November 29th to December 8th, the circulation of the air in the South-east Incline district was again suspended for the purpose of testing the district for fire-damp. When the stoppings were removed, and the ventilation restored, Mr. J. S. Martin, H.M.'s Inspector of Mines for the South-western district, renewed his inspections, and has reported as follows:—"A good deal of 'Black Damp,' 'Foul,' or 'Stythe,' had accumulated, so that at first we were unable to reach the Incline. The lamp was extinguished on the return side when put near the seat of the stopping, and it took two or three hours before we were able to examine the face of the workings. There was then, as before, not the slightest trace of fire-damp discernible in any place in the mine."*

* Report on the Circumstances Attending an Explosion in the New Pit, Camerton Colliery. By Joseph S. Martin, Esq., H.M.'s Inspector of Mines (p. 4).

This experiment, though made to test the mine for fire-damp, showed the important difference in the character of the gases that filled the roads after the explosion, as compared with the normal gaseous exhalations of the workings. In the former, the lights burned brightly ; in the latter, the light was extinguished, affording characteristic evidence of the presence of carbon dioxide gas.

During the ten hours that intervened between the explosion and the re-establishment of the circulation of the air in the South-east Incline district, it may have been expected that the carbon dioxide gas, which was subsequently proved to be normally exhaled from the strata of the workings, would have diffused into the gaseous mixture that filled the roads and inclines after the explosion. The absence of any trace of carbon dioxide gas upon the lights of the exploring party, therefore, becomes more significant with the evidence of this experiment.

The exploring party do not appear to have observed any variation in the nature of the stagnant gases ; and though they may have become homogeneous at that time, they could not have been so immediately after the explosions. The aggregate length of road traversed by the explosions was 1,775 yards. If it be assumed that combustion of the explosive gas proceeded to the limits of mechanical violence upon either side of the centre of ignition, then the products filled 697 yards ; while the intervening spaces, representing 1,078 yards, contained the products of the activities which commenced in the distillation of gaseous hydrocarbons from the coal-dust. These non-explosive spaces could not have been vacuous, as in that case carbon dioxide gas would have diffused into them from the strata, and the suggestion of a vacuum is precluded by the explosions that occurred adjacently. The ultimate atmosphere in the roads was the products of the explosive combustion of gases, plus the gases remaining after inexplosive chemical actions.

The composition of this ultimate mixture of gases is at present a speculative question, but it is a significant fact that carbon dioxide gas could not be detected in the path of the explosions, and as that gas is an essential product in the explosion of hydrocarbon gases, and is readily discoverable after their combustion, it is clear that as in the initial, so in the propagated explosions, the explosive phenomena was not produced by the ignition of those gases. The carbon suspended in the stagnant gases, and, which was deposited on the walls of the mine throughout the course of the explosions, shows that the distilling action in the coal-dust, and the decompositions of the hydrocarbon gases evolved, which were traced antecedently to the initial gaseous explosion, were in active progress throughout the propagation. This dissociated carbon is also distinct evidence that the remaining gaseous constituent, hydrogen, was the gas evolved in these decompositions, and formed the explosive gas in the repeated explosions.

A distinct feature in the explosions is the limitation of the sound they produced. The four men engaged in the New Branch district received their air from the current in the Horse Road by the split at Probert's Dipple. No. 6 Explosion at this point was very violent, and its mechanical effects extended 100 yards down the dipple. The transmission of the sound was aided by the current; but it never reached the men about 400 yards away. These men were also about 400 yards from No. 8 Explosion at the Pump Corner, where the violence was exerted 50 yards into the New Branch towards them; but they heard nothing. When No. 10 Explosion occurred at Tom's Road, there was a man at the bottom of the Downcast shaft, distant about 946 yards in a straight line; but no sound reached him, though a wave, propelled by the explosion, affected his light. A pony driver was, at the same time, standing between the Downcast shaft and Tom's Road in the Main Intake at the

Middle Vein Junction, about 616 yards from No. 10 Explosion, and heard nothing. Sound is also heard for considerable distances in mines by the conduction of the strata ; but probably the faults here, broke up the transmission. All these men were practically within reach of the sound of the explosions, supposing that they compared with explosions of a similar extent in gaseous mines. The sound of gaseous explosions has been compared to a distant cannonade, or the reverberations of earth tremors ; but nothing of that character occurred here.

The mechanical effects upon the air-current were limited. There were two observers, the pony driver at the Middle Vein Junction, and the man at the Downcast shaft. The driver was in the Main Intake when the explosion occurred at Tom's Road, and simply felt a puff of wind that blew his light out, and he thought no more of it until he heard of the explosion subsequently. The man at the shaft states that he saw the flame of his oil lamp reverse towards the pit for a moment, and then resume its normal position, but it was insufficient to excite suspicion that anything unusual had occurred, and he attributed it to the opening or closing of a door. The reversal of the current was probably an impression due to its momentary arrest, by the explosion at Tom's Road. There was only a local displacement of air at the point of explosive ignition.

The absence of sound, and the non-displacement of the air-current, are evidences opposing the suggestion that there was absolutely but one explosion, and all the exhibitions of violence the result of one instantaneous action. An instantaneous and cumulative explosive in 1,775 yards of tortuous roads in a mine, must necessarily have driven the air-current out of the Downcast shaft, distant only 946 yards, and have been heard by the pony driver and the man at the shaft with alarming distinctness. The facts that the air was not so displaced, and the explosion not

heard, are consistent with the direct evidence in the workings, that each section of violence represents a distinct explosion, and each section without violence the distance and period between each explosion. The failure in the transmission of sound coincides with the suggestion that they were detonating explosions, in which intensity of sound is limited by virtue of the small amplitude of the vibrations.

The falls and dislocations have hidden or obliterated most of the evidences which the sections may have yielded as to their individual character, but at Probert's Dipple some remained, and they were definite. Referring to Plate IV., Fig. 17, there were four timber collars A, B, C, D between the dipple and the Incline, all of which had coked dust on their outside faces towards the dipple, but none on their inside faces. On the opposite side of the dipple, and in the fall, there was a timber prop (E, Fig. 15) standing, with coked dust on its inside face, but none on the outside. With coked dust on the opposing faces of these timbers, on either side of the dipple, there can be no reasonable doubt, that it was driven there by the development of a force between them, which exerted itself in opposite directions. That force was limited and local : absolutely separate from the force that preceded it 164 yards behind, at the Incline on one side ; and that which succeeded it, at 460 yards away at No. 7 Explosion, on the other side. In the outer end of No. 7 Explosion, small scales of stone were driven into the inside face of a prop (F, Fig. 11) indicating the force was on that side, and localising it in the falls. The explosive energy at the Pump Corner was exerted entirely at right angles to the Horse Road in which the explosive gas had been generated. The mechanical violence at the Manhole, and at Tom's Road, was developed exclusively in roads at right angles to each other, localising the explosive ignitions at their junctions.

The exhibitions of violence upon elastic and movable objects in
G 2

Nos. 1, 2, 3, 6, 8, 9 and 10 Explosions could only have been effected by local and detonating explosions. Had there been one continuous explosion, these objects would have been swept away and probably broken; not shattered to fragments. In the sections of violent energy the roof was broken down alike in friable strata, requiring double timbering, and in firm strata needing only occasional props. The power developed was adequate to rip down bedded stone to a height of three and four feet, and the limitations of these disruptions to intermittent sections, with the roof of the intervening spaces undisturbed, isolates and localises the force engaged. The propagation of the explosions by the repeated generation of volumes of explosive gas, and their ignitions in succession to each other, separated by the gas generating intervals, are therefore facts of observation.

The Author suggests the following as the history of the activities which produced the effects that have been observed.

The explosion of the gunpowder produced sufficient heat to bring about the series of physical and chemical activities, which closed with the gaseous explosions at the air-pipe and centre wheel. The heat produced by each of these explosions was adequate to produce a similar chain of consequences, each successive explosion being alike productive in the propagation.

The question to be considered is whether these subsequent gaseous explosions evolved products at a temperature capable of renewing the activities by which they were themselves produced.

The lower end of the South-east Incline, and the adjacent siding with the loaded trams of coal, are shown in Plate IV., Figs. 19 and 20, and upon an enlarged scale in Plate VII., Figs. 33, 34 and 35. The siding was 8 feet wide, and 6 feet high, timbered with posts and collars; and the loaded trams, with their open ends of exposed coal towards the

Incline, were upon the line of rails next to the deep side, the other line being empty. The back end of the last tram stood immediately under one collar, and the succeeding tram under the next (Fig. 35); and these collars were 6 feet long in the clear between the posts. After the explosion, the coal in the last tram was found disturbed; about 60 lb. had been apparently sheared off the end of the load, and the opposing faces of these two timber collars were coated with matted, cindered coal-dust throughout their length. There was none upon their other faces, nor elsewhere in the siding. The evidence was definite that the coal had been attacked, displaced, and subjected to some amount of destructive distillation, and that intumescent portions had been carried up to the roof and detained by the exposed faces of the collars. This cindered coal-dust was in the same condition as that found on the Prop H (Plate VI., Fig. 31); and the action of the heated gases that produced it, showed that their temperature approximated to that of the products of the exploded gunpowder, inasmuch as they produced the same effects.

This phenomena occurs in the midst of the explosions, where no shots were fired, and where the only possible source of heat was the preceding gaseous explosion. Tangible evidences are therefore provided that heated gases emerged from No. 5 Explosion, and caused No. 6 Explosion at Probert's Dipple, in the same way that the products of the shot produced Nos. 1 and 4 Explosions, at the air-pipe and the centre wheel.

There are several features in the siding at the bottom of the South-east Incline and its vicinity, from which something may be gathered of the nature of these heated gases and their action.

It will be recollected that the effects of the heat of the exploded gunpowder ceased to be visible below No. 4 Refuge hole, where the deceased men were burnt, but that there remained many potent energies

in existence, was demonstrated by the explosion at the centre wheel, where there still remained an amount of residual or supplementary heat adequate to bring about this explosion.

At a distance of 330 yards beyond the shot, in the siding at the bottom of the Incline, and in the midst of subsequent explosions, visible effects of heated gases again appear, showing that they were present throughout the intervening length of Incline and Horse Road.

The siding where the tram stood had a sectional area of about 45 square feet; the end of the tram itself contained less than 6 square feet; it was near to the side, and presented practically little obstruction, so that the gases had ample space to pass freely (Plate VII., Fig. 34). The heated gases seized upon the combustible contents at the open end of the tram. The first 9 inches of coal, measuring from the bottom of the tram, was wedged in and left undisturbed, but at that level, which was about 18 inches above the rail, the coal, which in size of pieces would compare with screened coal, was removed on a rising slope. The tram was 2 feet 6 inches wide at the top, and the timber collars at the roof extended laterally 3 feet 6 inches beyond it over the parallel line of rails. The matted and cindered coal-dust was not only upon the portion of the timber collars immediately over the coal in the tram, but over their entire length (Plate VII., Figs. 33, 34), showing that the gases filled the whole sectional area of the siding. Such was the volume of gases that emerged from No. 5 Explosion, which on reaching the bottom of the Incline were face to face with the side of the Horse Road, and were momentarily split, one portion going inbye, the other outbye to the siding.

The side of the Horse Road here presented a face of at least 50 square feet of argillaceous strata. If these gases had been in a condition of "Flame," that is to say, hydrocarbon gases undergoing combustion, the immediate front portion, when it impinged upon this face of cold

strata, must have surrendered heat and deposited its carbon. If the heated gases were preceded by a cloud of dust, heated particles of that dust must also have been deposited when they collided with this side of the Horse Road. There were no deposits of carbon or of cindered coal-dust on this face of strata.

The Horse Road inbye was blocked with débris and loose timber, on one piece of which there was a little cindered coal-dust. The remainder of the timber was partly shielded, and had fine coal-dust upon it which was perfectly soft and impalpable. The cindered dust referred to, was, no doubt, originally upon this timber collar as impalpable coal-dust, like that on the other timber there ; and was cindered by the hot gases impinging upon it, when they momentarily turned in that direction.

The Horse Road outbye was free from obstructions ; the gases, therefore, re-united, and proceeded wholly in that direction, the tram of coal and siding retaining the evidences of their action and progress. The first impression received on seeing the tram and its disordered coal (Plate VII., Figs. 34, 35), was that it had been subjected to a violent rush of gas from the Incline, exceeding the velocity of a hurricane ; but there was no other indication of such a force in the siding ; on the contrary, the evidences there pointed to tranquil conditions, and the trams were standing freely upon the rails in their original positions. If the condition of the tram had been brought about by a mechanical force, such an amount of energy against the exposed end, must have driven the trams along the rails out of the siding. The dislodgment of the coal presents no difficulty when it is remembered that the gases were at an exalted temperature. These hot gases, advancing against the exposed coal in the open end of the tram, would fill the interstices of the load, permeating the mass and penetrating the lumps, causing an instantaneous expansion, reducing the coal to a pasty, intumescent condition, distilling

out its gases, and leaving a matted mass of coked residues, similar to that found upon the timber collars immediately over these activities.

Attention must be drawn here to the important fact, that the coal in the tram which was subjected to this action was in lumps of from a quarter of a pound to at least four or five pounds in weight ; and their residues are matted particles, closely resembling the residues of coal-dust on the props near No. 2 shot in size, form, and thickness of deposit. It therefore appears that coal-dust in a fine state of division is not an essential condition to the propagation of an explosion. When an explosion has been initiated by the explosive combustion of gases evolved by coal-dust, a volume of highly-heated gases emerges from the seat of that combustion, capable of distilling hydrocarbon gases from lumps of coal. Fine coal-dust presents a larger surface for distilling action, and would consequently yield gas more rapidly than lumps of the character under notice ; but it would not be prudent to conclude that that action would be stopped because the coal-dust changed into coarse particles ; nor must it be concluded that coal-dust which has been exposed to the action of air-currents, is essential to the propagation of such an explosion. Although the gaseous body that emerged from the explosive combustion in No. 5 Explosion, had no disruptive mechanical force excepting at the *loci* of explosion, its high temperature, and properties of producing intense chemical energies in carbonaceous matter, constitute it a grave danger ; whose object lesson is in Nos 6, 7, 8, 9, and 10 Explosions, of which it was the progenitor.

It is now known as a fact that a volume of highly-heated gases emerges from each explosion, with potentiality to repeat the explosive phenomena, and that there is an interval between each explosion, in which the gaseous mixture for the next ensuing explosion is generated.

The successive gaseous explosions occurred in large sectional areas

of roads, or contiguous thereto. When the gases emerged from an explosion and its section of violence, they exerted no disruptive force while passing through a considerable length of the ordinary-sized road, but ignited with violence on reaching enlarged sections or directly after passing through them. There were some apparent exceptions, which will be examined.

Taking the explosions in order, No. 1 followed immediately after the wide landing and old junction at the bottom of No. 2 Incline. Nos. 2 and 3 Explosions in the landings and junctions at the bottom of Nos. 3 and 4 Inclines. No. 4 Explosion immediately following the passbye and changing station at the centre wheel. No. 6 Explosion at the junctions of Probert's Dipple and the Great Vein Branch with the Horse Road. No. 7 Explosion immediately following the passbye and meeting-place in the Horse Road. No. 8 Explosion at the junction of the Horse Road and Main Intake. Nos. 9 and 10 Explosions at old junctions at the Manhole and Tom's Road.

There was the double rail landing, 56 yards from the shot, and at the top of the South-east Incline ; and the siding at the bottom in the Horse Road, which are exceptions to the ignitions ; and No. 5 Explosion which occurred in the ordinary-sized road. The failure of the gases to ignite at the top of the South-east Incline was because they had not at that time attained the conditions of ignition, but which accrued in the succeeding large section, 60 yards further. The absence of ignition in the siding at the bottom of the South-east Incline, was evidently due to the same cause ; the gases having at the moment emerged from No. 5 Explosion, and only just commenced to generate the gases that were necessary to produce an explosion. No. 5 Explosion is an exception, and its examination will be deferred until the relation of this rule to the ignitions can be considered.

The explosion was propagated up the Inclines for 276 yards with the air-current measuring a volume of 6,000 cubic feet per minute; down the Incline and along the Horse Road to Probert's Dipple 474 yards against the air-current of the same volume, producing effects down Probert's Dipple 100 yards with the air-current of 1,500 cubic feet per minute; and from Probert's Dipple to Tom's Road 717 yards against an air-current of 7,500 cubic feet per minute.

At the extreme ends of the explosions, towards the coal-faces in one direction, and the Downcast shaft in the other, there were adequate circumstances to account for their termination, but no such causes existed for the failure in propagation from Probert's Dipple into the New Branch district; through the Great Seam Branch to the workings beyond; through the Manhole door, and through the doors at Tom's Road into the Return airways. Dust prevailed in these workings and roads in the same condition as that in the Horse Road, and elsewhere where the explosions occurred, and therefore with the absence of propagated explosions in them, it is obvious that coal-dust is not the sole condition of propagation.

It will be observed there was a considerable difference in the violence exhibited by the repeated explosions with the air-current and against it, other things being equal. The destruction produced by the explosions up the Inclines with the air-current, bears no comparison with that effected down the Incline against the current, which was 6,000 cubic feet per minute in both cases. The explosion at Probert's Dipple failed to propagate itself through the dipple workings, in an air-current of 1,500 cubic feet per minute; but it was propagated against the larger current of 7,500 cubic feet per minute towards the Downcast shaft. In the absence of conditions in the coal-dust to account for such diverse phenomena, recourse must be had to the air-current for an explanation.

During the explosions, the pressure of the Intake current remained practically constant. The explosive gases travelling with, and therefore in a receding air-current, could not obtain an equal supply of atmospheric oxygen, as when they were travelling against the air-current, and into a constant supply. It has been observed that the explosions were repeated in strong currents of fresh air, and that propagation failed in a feeble current, and in the Return airways. The obvious difference in the condition of the ventilation in these circumstances, is the relative volumes of available atmospheric oxygen for the oxidation of the explosive gas. In a feeble current the gas would have to travel a considerable distance to get its necessary oxygen, meanwhile losing its heat. The Return air would be vitiated by the products of the oxidations that had proceeded during the circulation at the expense of its oxygen, and by the exhalations of the mine, and therefore would be in a comparatively unfavourable condition to oxidise an explosive gaseous body. There must necessarily be some relation between the phenomena of explosive combustions, and the volumes of oxygen to which the combustions are due. The difficulty that presented itself in one of the conditions of the coal-dust theory, that the explosion should travel all dusty roads equally, which made coal-dust the sole factor, is removed in the appreciation of the fact, that propagation can only proceed in coal-dust when an adequate supply of atmospheric oxygen is available for the oxidation of the gaseous body, before its residual or supplementary heat falls below its ignition point. The diverse phenomena in the several explosions at Camerton are, therefore, not only accounted for; but such diversity is intelligible. It is obvious that an explosion from the gases evolved by coal-dust, can only be propagated in dusty roads in fairly strong currents of fresh air, and the potentiality of the gaseous bodies formed will be greater when those

bodies are produced in advancing against the current, than when travelling in it, other things being equal.

This part of the question is further elucidated by observing the circumstances of the roads, where the ignitions of the gaseous bodies occurred. It has been already observed that the explosive combustions can be traced in enlarged sectional areas of the roads, or immediately following them. The advancing gases, on emerging from the normal-sized roads into these larger places, would suddenly receive the greater supply of atmospheric oxygen they contained, which presumably completed the quantity necessary for the oxidation of the hydrogen, inasmuch as combustion immediately followed. This occurred when the gases were travelling either with the current or against it, but it will be more readily understood if the latter circumstance be considered. When the gaseous body advanced against the current, the volume of air opposed to its progress became concentrated. Resisted in front and impelled from behind, the air would swell into the larger areas of the road, and form abnormal accumulations in them, ready to complete the oxidation of the gaseous body when it arrived.

The only apparent exception is No. 5 Explosion in the bottom end of the South-east Incline, which was not preceded by an enlarged section of road. The exception, however, disappears when it is remembered that the South-east Incline is approximately at right angles with the Horse Road, and at their junction, the Incline has a large sectional area forming its bottom landing. The air-current opposed by the gaseous body travelling down the Incline, and propelled forward by its own momentum, would become cushioned and accumulated in the lower end of the Incline in the face of the advancing gases, and conserved there by the resistances set up in the angle, against its escape. The same condition of an accumulation of air would therefore prevail here as

obtained at the junctions, passbyes, and the Pump Corner, and provide the necessary accession of oxygen to perfect the conditions of an explosive combustion. In regard to the large areas of the sidings at the top and the bottom of the South-east Incline, where no combustion ensued, it is now clear that the gaseous bodies on reaching these points had not obtained sufficient oxygen for that purpose; nor is it surprising, seeing that the first gaseous body from the shot, had to travel much more than double the distance down the Incline, against the current, before its oxidation became possible. There may be other conditions set up in the gaseous bodies in passing from small into large areas, but probably the accession of oxygen thus obtained is the chief factor.

The trams were changed at all the suggested centres of explosive ignition, save two, the Manhole and Tom's Road, and the concussions that arise in stopping and starting a tram or journey of loaded trams, causes an additional leakage of coal at these points; but the two exceptions named, show that there was sufficient coal-dust in the ordinary roads to yield violent explosive phenomena.

Another feature in the propagation of the explosions, was the displacement of timber, and the scaling of the roof, in sections of road between the explosions, which contained no evidence of violence. This occurs, more or less, throughout the roads traversed by the explosions. The superficial and general character of this scaling showed that it was referable to actions diverse from those that produced mechanical violence, which in other places ripped the same class of roof for several feet in height; but the displacement of the timber appeared to necessitate an explanation involving mechanical energy. The probable solution of this phenomena is to be found in the gaseous bodies that travelled through the roads. It will be remembered that the gaseous body immediately produced out of the coal-dust by the products of the gunpowder shot,

was of a very high temperature, as shown in its effects at Nos. 2 and 4 Refuge holes; and that the gaseous body that emerged out of the No. 5 Explosion was also of an exalted temperature. In both cases it was observed that they filled the entire sectional areas of the roads, and were intensely hot next to the roof, upon which they must have necessarily impinged, and thereby set up an action analogous to the old method of breaking rock by fire and water. The faces of the roof would be heated up by these impinging gases, and afterwards subjected to the ordinary temperature of the mine; expansion and contraction were thus produced; and where the strata contained moisture, or was cut up by joints, or thin-bedded, scaling would naturally follow, unlocking the timber and props, and consequently they would fall to the floor. Between Nos. 6 and 7 Explosions there was a length of timbering measuring 34 yards, all of which was displaced, which displacement seemed to be the result of violence. The strata of the roof were, however, only scaled, and when it is considered that the advancing gaseous body would meet with greater frictional resistances in passing through timbered sections, as compared with the natural sides of the roads, which would detain them, causing the hot gas to envelop the faces of the timber and play upon the strata, the action that has been suggested becomes conceivably adequate to account for the unkeying and collapse of the timbering.

The difficulty in realising that these gases travelled through the 460 yards of road between the ignitions of Nos. 6 and 7 Explosions, with the immense extent of cooling surfaces, without a loss of temperature fatal to their ignition, is lessened in the fact that after they passed through the first quarter of the distance, they were at an exalted temperature, which, by simply impinging upon the strata between the timber collars, produced the displacement of 34 yards of timbering. The continuation of this scaling action at intervals throughout the remainder

of the distance, and ultimately the ignition of the gaseous body generated *en route*, complete the evidence that either a quantity of heat was generated in No. 6 Explosion, or in secondary actions that were produced by its heated products, adequate to cause the effects observed, notwithstanding the demands made upon it by the large area of cooling surfaces, exclusive of the expenditure in chemical activities.

The scaling affords the remaining evidence of the general travel of the highly-heated gases throughout the path of the explosions.

The varied phenomena of the propagated explosions have now been examined. They present a remarkable freedom from opposing or complicated features, and possess a definiteness of character. The views which have been advanced to account for them would appear to make the propagation of explosive phenomena by the gases evolved by coal-dust a conceivable operation, to which the discussions which will form the subject of the following chapter will, it is conceived, lend additional strength.

DISCUSSION OF THE EXPLOSIONS AND CONCLUSION.

THE discussions which have engaged attention in the preceding chapter have dealt with the observed properties of the gases that must have been present, and the products of the various physical and chemical energies to which they had been subjected. These properties may be thus summarised :

- (a) The products of the gunpowder explosion were of high temperature.
- (b) The high temperature was adequate to generate gases from coal-dust, to decompose some of those gases, and to evoke secondary activities which had for one of their results the provision of additional heat.
- (c) The gaseous bodies were able to command a second ignition after passing through long lengths of road with extensive cooling surfaces, by virtue either of residual heat, or of heat generated in supplementary actions.
- (d) The conditions of explosive combustion were perfected when the gaseous bodies passed from normal sections of road into larger sectional areas.
- (e) The explosions were accompanied with detonating violence.
- (f) The air-current was only displaced locally in the explosions.
- (g) The transmission of sound was limited.
- (h) Carbon dioxide could not be detected in the gases that filled the roads after the explosions.

- (i) Heated gases were evolved out of the explosive ignitions of the gaseous bodies produced, adequate to propagate further explosions.
- (k) The explosions were propagated in the presence of coal-dust and adequate atmospheric oxygen.
- (l) The propagation was arrested in "Return" and in feeble air-currents, in the absence of dust, and in damp and wet road.

The origin of the explosions is marked by the effects of the products of the exploded gunpowder upon the coal-dust in the vicinity of the shot. Gases were evolved from this dust, and formed the gaseous bodies, to the ignition of which the initial gaseous explosions were due ; and these explosions were propagated at varying intervals for considerable distances.

The actions that proceeded from the moment the products of the exploded gunpowder reached the coal-dust, up to the initial gaseous explosions must now be considered.

The first inquiry is as to the quantity of heat available in the combustion of the gunpowder in No. 2 shot. The total quantity of heat generated by that charge has been already determined, upon the experimental researches of Sir Frederick Abel and Captain Noble, to be 183,141 gramme units, from which must be deducted the amount consumed in the mechanical force that ruptured the rock. Judging from the nature of the strata, the quantity of stone dislodged, and the effects produced by what was practically a similar charge in No. 1 shot, the actual work done by No. 2 shot may be fairly stated at less than one-fourth of the capabilities of the gunpowder employed. It may therefore be assumed that, after allowing for the expenditure of heat involved in work done, there remained, in round numbers, 140,000 gramme units

available for the physical and chemical activities to which the initial gaseous explosions must have been due.

The centres of the initial gaseous explosions have been localised at distances of 136 yards and 140 yards respectively on opposite sides of the shot. Referring to the explosion on the lower side of the shot, evidences have been given that the gaseous mixture which passed the Refuge holes numbered 2 and 4, and which must have been made up of the gaseous products of the ignited gunpowder, and the gases evolved from the coal-dust by the action of the heat conveyed in the gaseous and solid products of that gunpowder, was of a high temperature, as was observed in the effects upon the food bag, and on the deceased men. It has also been shown that these gaseous bodies, after they had an adequate addition of oxygen to produce an explosive mixture, could not have exploded if their temperature had fallen below 650° C. unless they were brought into contact with an adjacent body possessing that temperature. The actual temperature of the products of the exploded gunpowder in the conditions that obtained, has been already estimated, upon the experimental researches referred to, to be at least 2,231° C., which shows a difference in the temperature of the products at the moment of their expulsion from the shot hole, and the temperature of the mixture of gases in which the explosions occurred, at distances of 136 and 140 yards, of about 1,600° C. This range of temperature accounts for considerable distillatory action in the coal-dust.

The coal-dust from which this gaseous mixture was distilled, was in a favourable condition for the process, and would yield up its gases at a minimum expenditure of heat. It was in a state of fine division, presenting the maximum of exposed surfaces to the distilling action ; it was also dry, and consequently it had already undergone a desiccation which, in the gas retort, is obtained at the expense of considerable heat. The

quantity of heat required in ordinary gas distillation to produce identical results with those yielded by this coal-dust, was not necessary here; in other words, the dust would need a less quantity of heat, and a shorter period of exposure, to yield an equal quantity of gases with the process in the gas retort.

The heat available for the actions under consideration has been fixed at 140,000 gramme units, of which 74,144 units are held by the gaseous products and 65,856 by the solid residue. The solid residue has been referred to as being in a fluid condition, but at the temperature of explosion which has been discussed; and with liberty to expand indefinitely, this residue would be ejected in a state of fine division, and in that condition would be projected into the coal-dust in the vicinity of the shot. Its stored heat would consequently be localised in that neighbourhood, and undoubtedly produce important chemical actions in the coal-dust there. It is, therefore, to the gaseous products that attention must be turned for a supply of heat to prolong the activities from the immediate vicinity of the shot to the initial gaseous explosions; and this supply is represented by 74,144 gramme units.

If the initial gaseous explosions were solely due to the available heat generated by the gunpowder in the shot, then the 74,144 units must have performed the following work. They must have

- (a) Raised $\frac{52.96}{100} \times 354.375$, or 187.677 grammes of the charge of gunpowder to the temperature of the ignition of the gaseous mixture.
- (b) Generated a gaseous mixture from the coal-dust.
- (c) Raised a portion of the evolved gases to the temperature of ignition.
- (d) Raised the volume of air required for this ignition to the igniting temperature.

The specific heat of the gaseous products in the combustion of one gramme of mining powder was determined by Sir Frederick Abel and Captain Noble at .09553.* The first computation, therefore, is

$$187.677 \times .09553 \times 650 = 11,650 \text{ gramme units of heat.}$$

The second item can only be conjectured, in the absence of evidence as to the quantity of gas generated, and it will be sufficient for the demonstration that is being attempted, to assume a certain volume was evolved, and proceed to the next computation. In estimating this volume, it is only necessary to consider that portion which was oxidised with explosive violence, that is to say, the hydrogen, inasmuch as this gas must be first satisfied with the oxygen present before any other of the gases could get supplied, and consequently the initial gaseous explosions must have been the result of its oxidation. The gas generation proceeded over 140+136 yards of the Incline, representing about 5,000 square feet of floor surface; and allowing $1\frac{1}{2}$ oz. of dust only per square foot as having been subjected to distillation, there would be 468 lb. of dust, yielding gas. The coked residues, however, showed that the distillation was not absolute; and allowing for this partial disengagement of the gases, and the volume of hydrocarbon gases that would remain undecomposed, it will be quite safe to assume that there was 1,000 cubic feet of hydrogen gas produced, which could be obtained from less than 2 cwt. of the coal by destructive distillation. This volume of hydrogen, which affords 500 cubic feet for each of the initial gaseous explosions, had to be raised to the temperature at which oxidation takes place, viz., 650°C. , and the quantity of heat demanded for that purpose can be ascertained. The weight of 1,000 cubic feet of hydrogen at 0°C. and 760 mm. bar. pressure is

*Philosophical Transactions, Vol. 171 (p 228).

2535.68 grammes. The specific heat of hydrogen at equal weights, water being unity, is 3.409, therefore, $2535.68 \times 3.409 \times 650 = 5,618,686$ gramme units of heat would be required under this head of the activities.

It is unnecessary to go into the complex calculations involved in assessing the quantity of heat that was used under head (b) to generate the gases, nor into the simple computation of determining the heat under (c) which was needed to raise the 2,500 cubic feet of air used in the oxidation of the hydrogen to the temperature of ignition. It is sufficient to observe that the heat required by the activities under heads (a) and (c) alone are $11,650 + 5,618,686 = 5,630,336$ gramme units, while the available quantity from the gunpowder charge is 74,144 units. The absolute incapacity of the gunpowder in the shot to produce the initial gaseous explosions, is therefore mathematically demonstrated; consequently another source of heat must have been brought into requisition.

It is indisputable that the heat in the products of the gunpowder originated the activities under discussion, and an endeavour must now be made to discern the additional agencies which contributed to the result. Returning to the shot, and recalling the phenomena of the products of the powder projected in fan-like sheets down a series of planes into the coal-dust, it will not be difficult to trace actions that may have followed. It will be remembered that all the hydrocarbon gases evolved from coal are decomposed at temperatures below $1,500^{\circ}$ C., and that the temperature of the products of the gunpowder is over $2,231^{\circ}$ C. at the moment of their projection from the shot hole. The immediate effects produced by these solid and gaseous products at such an exalted temperature, being projected at a high velocity into the coal-dust, must have been the evolution of hydrocarbon gases, and their dissociation at the moment of liberation, yielding free hydrogen and depositing the carbon; and this action would proceed within a limited distance from the

shot. The processes could only proceed at the expense of the heat stored up in the gunpowder products, and with this expenditure and other demands, their temperature would rapidly fall below the point at which decomposition could take place. When this lower temperature was reached, there would still be a distilling heat; hydrocarbon gases would continue to be produced, and if they could obtain oxygen that was not within the reach of the separated hydrogen, they would now undergo more or less combustion. The propulsive force with which the products of the gunpowder were projected from the shot hole into the atmosphere of the Incline, necessarily drove the air away from the immediate vicinity in which these activities were in progress, but there would remain residues of air in interstitial spaces and in side openings, which would diffuse into the Incline after the first rush of the projected gases. In No. 2 Refuge hole, and at 4 feet distant transversely from the side of the Incline, the deceased men's shirts were upon a piece of timber on the floor, and were not affected by the hot gases, so that the air was evidently cushioned in this hole, and resisted the expansion of those gases beyond the food bag, and after they had passed, this compressed air would escape into the Incline. The same thing would occur from the old road opposite No. 2 Refuge hole, and from the interstitial spaces in the coal-dust and débris, and walls of the Incline. This supply of atmospheric oxygen would be limited, but it would suffice to bring about a correspondingly limited ignition of hydrocarbon gases which would be evolved from the coal-dust, when the temperature of that dust had fallen below the temperature first communicated to it by the products of the shot.

The phenomena presented by this ignition, would resemble, but in a less degree, the tongues of flame rising off coal-dust, referred to in the introduction of this volume. There is evidence that this phenomena did exist in one of the explosions—viz., that at Tom's Road. The dust

in that road was very dry and mobile. On the lower portion of the standing leg of the inside door-frame, there were fantastic and sinuous markings, slightly darker than the wood. This colour was due to the deposition of solid matter, and compared with that produced by allowing a flickering tongue of gas-flame to impinge lightly, and with intermissions, upon the surface of a hard wood. This door-frame was made of oak. The Author has no doubt that these markings were caused by some of the hydrocarbon gases distilled from the dust at that place becoming ignited, and burning with large forked and fluttering flames. These gases were burning in the Return air, which was very poor in oxygen ; and the necessary supply for their ignition could only be obtained from a considerable volume of that air, with a consequent extension of dimensions in the flame, and a flickering and intermittent condition. This evidence is important in elucidating the activities under notice, inasmuch as it shows, that at a certain stage and region of these activities, hydrocarbon gases became ignited, and that flame, to some extent, existed upon the surface of the dust upon the floor. The spot at which this flame commenced, must have been at the centre of the explosive ignition, and in the coal-dust with which the products of the explosion first came in contact ; and the continuance of the flames with the distillatory action, is seen in the markings made as they passed this door-frame, which was 20 yards from the centre of the explosion.

In the immediate vicinity of the shot there was a series of activities in which a gaseous mixture was produced. The front section of that advancing mixture would contain the gases that were evolved when the gunpowder products were projected into the coal-dust at their exalted temperature, and, presumably, were chiefly hydrogen ; but, as the temperature fell, the constitution of the gaseous mixture changed, and merged from hydrogen to hydrocarbons ; and some of these hydro-

carbons became ignited by obtaining oxygen from the sources before referred to.

Beyond the immediate vicinity of the shot, the temperature of the front face of this advancing mixture would fall below the point at which the decomposition of the hydrocarbons could proceed ; the production of hydrogen would become a diminishing quantity up to that point, because there would not only be a decreasing volume of gas due to destructive distillation, but this decreasing volume would be undergoing a lessened decomposition, according to the series of changes described by Professor Vivian Lewes ; and, in fact, the distillation would ultimately cease, unless the activities that are being recognised, were supplemented by others that will be referred to.

The undecomposed hydrocarbons, which, it is seen, must find a place in the gaseous mixture, will at the available temperature enter into combination with the limited amount of oxygen obtained from the small supplies of air afforded by the recesses already described ; and if the oxygen were adequate in quantity, carbon dioxide and water would be the products of the flame. But experiment was found to demonstrate that no abnormal amount of carbonic acid gas existed in the atmosphere of the mine immediately subsequent to the explosions. It follows from this, that the available oxygen was certainly not more than adequate to oxidise the hydrogen constituent of the hydrocarbons, and consequently the depositions of carbon which have been noticed on the walls of the workings throughout the path of the explosions, find one explanation : there was not enough oxygen present to burn this remaining constituent.

In endeavouring now to elucidate the supplementary activities which are found to have been essential to produce and ignite the gaseous mixtures of the initial gaseous explosions, the condition of the atmo-

sphere of the Incline in the immediate vicinity of the shot may be conceived to have been as follows :—There was a considerable amount of hydrogen at a high temperature, due to the action of the products of the shot, and a quantity of gaseous hydrocarbons, which the available heat had been inadequate to decompose. From the recesses, out of which the air had not been driven by the heated gases ejected by the shot and the gaseous bodies they produced from the coal-dust, a sufficient amount of oxygen would be supplied to sustain a feeble combustion of some of these products of distillation. This combustion would supply heat to continue the distillatory process in the adjacent coal, part of the products of which would escape into the superincumbent atmosphere, and part would be heated up to the point of ignition, to continue an advancing series of similar changes.

It will now be seen that a string of flames must have followed the first effects of the heated products of the shot upon the coal-dust ; and it will not be difficult to realise the energy of the supplementary activities they evoked, when it is recollected that the combustion of two grammes of the hydrogen constituent that produced those flames, in oxygen gas, generates 68,924 gramme units of heat.* In the computations of the quantity of heat required for the actions that produced the initial gaseous explosions, it was assumed that 468 lb. of coal-dust underwent distillation ; and the hydrogen gas that would be yielded by one-half of that quantity was taken to form the two gaseous bodies in those explosions. The remaining half of the coal will be taken to have yielded hydrocarbon gases, and that a portion of them underwent the combustion that has been described, in which the hydrogen constituent only was burnt. If it be assumed that that portion represented

* Bloxam's Chemistry, VII. Ed. (p. 38).

250 cubic feet of hydrogen from the shot to the initial gaseous explosion on one side, and a like quantity between the shot and the initial gaseous explosion on the other, the distances being approximately equal—viz., 136 and 140 yards respectively, the total volume of hydrogen thus oxidised would be 500 cubic feet, equal to 1,267.8 grammes. The oxidation of the 1,267.8 grammes of hydrogen would generate 44,104.476 gramme units of heat; and it follows, from these moderately estimated volumes of gas, that in the supplementary activities there was a quantity of heat generated, adequate to perform the work represented in the production and ignition of the gaseous mixtures, to which the initial gaseous explosions were due.

The effects of this combustion were not only the evolution of large quantities of heat, but also the constant production of explosive gases, which could not be ignited because the supply of oxygen was inadequate. But the volume of these gases at last reached a large space in the workings, where they found a copious supply of air; and as soon as diffusion had given rise to a mixture of the explosive gases with the minimum requirement of atmospheric oxygen, a source of ignition was found in the flame with which it was in contact, and an explosion resulted.

The physical and chemical activities between the ignition of the gunpowder in the shot and the initial gaseous explosions, have now been investigated, and the relation between the shot and those gaseous explosions established. It has been demonstrated that the products of the gunpowder were capable of initiating these activities in coal-dust, but that they were absolutely incapable of producing the explosions that followed. It is also shown that when once these activities were called into operation, they evoked supplementary energies, which perpetuated them over considerable distances, ultimately effecting explosive ignitions

in the gaseous bodies produced, and presenting the phenomena of the initial gaseous explosions, numbered 1 and 4.

The discussion of the explosions that were propagated subsequently will now present no difficulty. The temperature of the hydrogen flame burning in air is $2,024^{\circ}$ C., and that would be the temperature of the products of the oxidation of the hydrogen in the initial and subsequent gaseous explosions. These products would be wholly gaseous; but in volume and weight, and, consequently, in calorific value, they would greatly exceed the gunpowder products; and the gaseous hydrocarbons that remained unoxidised in the explosive mixture for want of oxygen, would now undergo decomposition at this exalted temperature, producing free hydrogen. It will therefore be readily conceived that the products of the oxidation of the hydrogen, gave rise to a series of activities similar to those which have been traced, and propagated the successive explosions, the details of which have been given.

The mechanical energy evoked in the ignition of a body of hydrogen and oxygen, may be illustrated in a familiar experiment in the synthesis of water. A soda-water bottle is filled with these gases, and a light applied to the open mouth, when combination takes place with detonating violence, often shattering the walls of the bottle into fragments. The mechanical energy exerted in the oxidation of the volumes of hydrogen that must have been present in each of the gaseous explosions, must therefore have brought about effects of considerable magnitude; and it will be readily conceived how violent local disturbances were produced, though the gases were unconfined. The extent of the disruptions in each explosion, and the effects of the mechanical violence upon movable and elastic objects, are therefore accounted for.

The propagation of the explosions was arrested in various directions, and the reason of this must now be considered. It is only necessary

to recall the conditions of the absence of coal-dust on the floor of No. 4 Incline, beyond No. 3 Explosion on one side of the shot, and the damp and wet ground in the Main Intake beyond No. 10 Explosion, on the other side, to perceive that the circumstances at these points were entirely unfavourable to the activities which have been discussed.

No. 6 Explosion was not repeated down Probert's Dipple to the workings beyond, and the reason is not far to seek. The gaseous mixture was produced and exploded in the Horse Road; therefore, the chief volume of the products would be propelled along the axis of that road; the dipple, with its angular resistances, would obtain only a limited portion, and, consequently, only a fractional part of the calorific value. The disturbances in the dipple were in enlarged areas, but very small in extent; and if they were due to violence caused by the explosive ignition of gases generated in the dipple, the quantity so ignited was exceedingly small, and therefore the calorific value of the products would be inadequate to originate activities in the dust in this direction. The air-current was a small and receding one, and in this feeble ventilation it is probable that the activities could not obtain an adequate supply of oxygen to propagate the explosion.

No. 6 Explosion was not propagated in the Great Seam Branch workings, as Nos. 9 and 10 Explosions were not propagated into their adjacent dusty roads. In each case these adjacent roads were ventilated by "Return" air, the axes of the Horse Road and Main Intake were at right angles to them, and the ends of those axes were in open spaces; the products of the explosions of the gaseous bodies were consequently chiefly propelled in the lines of the axes. Some portion would go into the adjacent dusty roads, and in Tom's Road it has been observed they were of adequate calorific value to generate gases from the coal-dust, and ignite them. This flame

differed from that in the activities that have been discussed. In the latter case, it was hydrogen burning, there being a limited supply of atmospheric oxygen, and the heat evolved is represented by 68,924 gramme units for each two grammes of hydrogen.* In the former case, it was a flame in which carbon was undergoing oxidation, and was a hydrocarbon gas probably of the olefiant series, in which 23,884 gramme units of heat only are produced by the oxidation of two grammes weight;† while the combustion was taking place in a large volume of impoverished Return air, in which the flame roamed to obtain oxygen, and lost a considerable amount of heat by conduction. The products of this combustion were carbonic acid gas, and water in a gaseous state, which would diffuse into the air, and, consequently, a condition would be rapidly obtained fatal to combustion, and the flames would die out. This explanation applies to each case, and though the apparent cause of non-propagation from No. 8 Explosion into the New Branch district was dampness and absence of dust, had dry dust prevailed, propagation would have failed for the same reason as that in the other cases. As a fact, there was no propagation of the explosion in "Return" air.

It will be of advantage now to inquire how far the conditions that were supposed to be necessary to bring about an explosion of the gases evolved from coal-dust in mines, existed in the case under discussion. The coal-dust theory requires the dust to be pure, very fine, dry, thoroughly mixed with the air, and suspended in it in a cloud. It suggests that the "Flame" of the initial explosive agent is carried by this "Pioneering cloud" of dust, and that there is a continuous combustion in the cloud; and the suggestion of distinct and intermittent explosions is rejected.

These conditions are difficult to understand as an explanation of the

* Bloxam's Chemistry, VII. Ed. (p. 38).

† Balfour Stewart's Heat (p. 342).

processes involved in the propagation of explosive violence in non-gaseous mines. The propagation of an explosion in such mines, is the repetition of the explosion, which necessitates repeated productions of the explosive gas. The suspended dust in the "Pioneering cloud" is the suggested source of these gases; but the action in this dust is described as "Combustion" produced by a "Flame," the dust being in intimate admixture with the air. In a cloud of coal-dust in that condition the distilled gases must on this assumption be consumed as they are produced, as well as the oxygen in the air; and consequently there could be neither explosive gas nor oxygen left, to repeat the explosion. The phenomena of such a cloud of dust, would be as it is described, "A rush of flame," but it could not produce the phenomena presented by the explosive combustion of gaseous bodies, which involves exhibitions of mechanical violence of the character presented at Camerton. The essential condition of propagation of an explosion, is the production and accumulation of successive bodies of explosive gases, and propagation must necessarily present the phenomena of intermittent explosive ignitions. This condition cannot be obtained by distilling the coal-dust while in intimate admixture with air, at a temperature at which the educts can enter into combination with its oxygen. It demands a process analogous to that in a gas retort, the subsequent admixture of the distilled gas with an adequate amount of atmospheric oxygen, and a residual temperature capable of producing ignition, or an adjacent source of heat to do so. The phenomena at Camerton present the evidences of these actions. There were no traces of this "Pioneering cloud;" and where it must have left distinct impressions, there were none. There were, however, distinct evidences that the dust on the floor at rest was subjected to distillation, and that the atmosphere for, from 12 to 15 inches, immediately above the floor, was laden with heated particles undergoing

distillation. The remaining sectional area was filled with the gaseous products yielded, which accumulated until there was a sufficient accession of atmospheric oxygen to produce an explosive mixture, when the explosion was repeated, and propagation proceeded again.

The coked residues showed that the coal-dust had been in a condition of intumescence, and there was nothing to suggest that fineness of division was essential to the distillatory action. At the siding in the Horse Road, lumps of coal of several pounds weight were subjected to distillation by the heat generated in the oxidation of the gaseous body to which the No. 5 Explosion was due; and coked residues were deposited on the timber collars over the trams. Fine dry coal-dust suspended in a cloud in the air had no existence as a significant condition in the explosion.

When the generating gases were moving with a high velocity, such as must have been due to the propulsive effects of the shot, coked residues were deposited on the bottom ends of the opposing faces of the timber; but when advancing at the diminished speed which necessarily followed increased distance from the seat of the explosion, they were evidently unable to prevent that deposition of the particles of coal, brought about by their own gravity. This deposition becomes clearer when it is remembered that the effect of the high temperature upon the coal-dust, would transform the particles into a pasty intumescent condition, causing them to hang together, so that the force of gravity would have greater predominance over the upward atmospheric resistance, and the diminished velocity of the gaseous movement would have a correspondingly diminished effect in sweeping them against any opposing surfaces. Consequently no deposition upon opposing surfaces could arise under these circumstances, and hence their absence, excepting in the immediate vicinity of the centres of explosive action.

It has also been suggested that the explosion displaces and beats back the air-current bodily ; that it traverses all dusty roads ; and would not be arrested by from 50 to 100 yards of wet road. These conditions did not fully obtain at Camerton ; the air-current was not displaced in the sense that the motive column was overpowered ; propagation failed to proceed beyond the entrances of many dusty roads ; and 53 yards of road partly damp, and the remainder wet, sufficed to arrest the explosion.

There were necessarily local displacements of the air-current at each explosion, but the aggregate propulsive power they developed was, for practical purposes, inappreciable at the Downcast shaft. In the Middle Seam, which was ventilated by a split off the Main Intake between No. 10 explosion and the shaft, some men were working at the time of the explosions, but they experienced no sensible effect upon their air-current, so that the propulsive force of the explosions was principally directed against the column of air in the Downcast shaft, and with no practical result. The constancy of the ventilating power of the mine during the explosions is explained in the circumstance, that at each explosive ignition, one-fifth of the volume of air required for the oxidation of the gas, was removed in successive productions of steam, undergoing eventual liquefaction by surrender of heat ; and this exhaustion restored the mechanical equilibrium of the current after each explosion. When the character of the explosions is considered with regard to the intervals of time and distance which separated them, and the removal of a considerable amount of the explosive gas, and of the oxygen of the contiguous air employed by it in the combustion (which produced steam that underwent almost immediate condensation), the absence of mechanical effect upon the ventilating power, can be understood.

Failure of propagation in equally dusty roads has been dealt with ; but its arrest in wet spaces requires notice. The lengths of wet or dust-

free spaces suggested as essential to stop an explosion, were necessarily drawn from experience in explosions where fire-damp was present, inasmuch as at that time there had been no explosion in a non-gaseous mine. The products of the ignition of fire-damp are largely composed of the oxides of carbon, with some water in a gaseous condition ; the oxidation of hydrogen produces only water in a gaseous state. These diverse products suffer widely different effects when exposed to wet and damp surfaces. An atmosphere of the oxides of carbon, would suffer abstraction of heat simply in those external surfaces that impinged on wet and damp faces of the enclosing walls and floor, and this cooled exterior skin would largely prevent further loss of heat, so that the temperature of the body and its residual heat may be preserved over a considerable distance. An atmosphere of water in a gaseous state impinging upon a wet or damp surface, undergoes an action analogous to that in the condenser of a steam engine ; the external stratum next to the cold wet surface is instantly condensed, leaving a vacuous space into which another stratum of the gas falls, and that is condensed, and the process is repeated until the whole of the steam is liquefied. The products of the oxidation of the hydrogen would, therefore, lose their temperature in damp and wet ground, much earlier than the products of fire-damp, other things being equal, and consequently it is not surprising that propagation was arrested in a non-gaseous mine in 53 yards.

It has been suggested that propagation would be arrested upon heated gaseous bodies emerging from normal sections of road into enlarged areas ; but the phenomena of the explosions that have been discussed, indicate that reliance cannot be placed upon such a circumstance as a condition of safety, and that the oxidation of the gaseous bodies was, in fact, brought about under just such a condition. It would also be unsafe to trust to impure coal-dust as a protection, as, in the

activities under review, there was a selective action, in which the carbonaceous particles were seized and distilled ; and the adjacent particles of non-combustible matter being heated up, sustained the process of distillation by surrendering to the coal the heat they had received, and for which they had no other employment.

Another feature is, that secretions of fine dust upon the timbers and higher parts of the roads were unnecessary to bring about the explosions ; practically, such secretions had no existence here ; and the dust that is indigenous to the floor of the roads of a mine proved to be the seat of the activities.

The phenomena of the Camerton Explosion, so far as the Author was able to investigate and observe them, having been given, the consequences that follow may now be considered. The important feature is the origin of the explosions at a gunpowder shot, and in the ordinary operations of the mine. The conditions of coal-dust existing at the shot, were undoubtedly favourable ; but the conditions prevailing at the origins of the propagated explosions, were the ordinary conditions of the mine ; and it is arguable whether, the contributory circumstances of pure coal-dust, and its favourable accumulation in the vicinity of the shot, were essential to the gas-generating process. There were no "Extraordinary circumstances" present : the shot-firing was an ordinary operation, the presence of coal-dust was a normal circumstance, and the work was being done by a competent man. The angle and declivity of the hole were such, that if the gunpowder were expelled, it would directly strike the dust ; but it was so placed in the judgment of an experienced miner. His judgment was upset to some extent by the hidden development of a joint which no miner could have discovered ; and he never contemplated the contingency of the limited rupture of the strata, and the expulsion of the exploded powder ; which in a greater or less degree is not an uncommon circum-

stance. In the presence of this explosion, therefore, conjecture upon the supposed innocuousness of a gunpowder shot in a dry and dusty non-gaseous mine, is at an end.

The circumstances under which this explosion occurred, were practically those ordinarily prevailing in a mine, and the special conditions of the coal-dust, which were supposed to be essential to produce such phenomena, proved to be unnecessary.

The expulsion of a fired explosive from a shot hole in mining operations is popularly denoted in the phrase "A blown-out shot." As the origin of an explosion may be due to what is understood by that technicality, it is important that there should be no misconception as to what is meant by it. If an explosive charge, say of gunpowder, fail on its ignition to rupture the coal or the strata, or to fracture the walls of the hole, it is wholly expelled out of the mouth of that hole, and its enormous temperature is available for physical and chemical activities in the coal-dust of the mine. That would be a blown-out shot; but it is an uncommon occurrence, and is not an essential condition to initiate an explosion. Something less will suffice to set up the activities that have been discussed—viz., an explosive charge which, upon ignition, has a store of heat energy unexpended, after rupturing the coal or strata; provided the heated products be immediately brought in their concentrated condition into contact with coal-dust. When a hole is bored it is intended to rupture the strata in certain directions, and loosen adjacent material, and upon that contemplated duty the amount of the explosive charge is determined. In the nature of the case, the amount of the charge is more or less conjectural, even after long experience; because the lines of least resistance are hidden from the eye, and joints and planes unexpectedly intersect the strata. If the miner fail to put sufficient explosive into his hole, he will either lose his charge and time

by getting no result, or it will rupture the ground in a manner that will not compensate him for his labour and the cost of his explosive. As a rule he will not incur these risks, but will rather place an excessive charge of explosive in his hole, and after the demands to overcome the resistances of the strata are satisfied, the remaining heat in the products, is available for other activities. This is not, literally, a blown-out shot, though the heated products will be expelled into the vicinity of the hole. If these products are scattered in planes of rupture, so that their propulsive energy is expended, and their temperature reduced, they become harmless; but if they are projected into coal-dust with their energy and heat unexpended, chemical activities are inevitable. A shot in which the explosive is only partly expended in breaking down the resistances of the strata, is therefore partially blown out; but the point at which danger arises by the partial employment only, of the energies of the fired explosive, when the products retain a potency for originating dangerous activities in coal-dust, is undeterminable. The shot at Camerton was only partially blown out; that is to say the walls of the hole were fractured, and the products were projected through the area of rupture into the coal-dust; therefore upon that important fact the conclusion must be drawn that a grave danger may arise from a partially blown-out shot.

The circumstance that gunpowder was the explosive agent in originating the Camerton explosion must complete the evidence for the necessity of the rigorous employment of most careful precautions, where its use is resorted to in dry and dusty places in coal mines. In the character of its products there is undoubtedly a dangerous element in the heat, of which its gaseous and solid products are the vehicles.

It will be evident from what has been advanced, and recalling the character of the heated gases that emerged from No. 5 Explosion and

propagated the remaining explosions from that point towards the Down-cast shaft, that any explosive yielding gaseous and solid products, or gaseous products alone, would effect identical results with those caused by gunpowder, if its explosion afforded an equally effective source of heat.

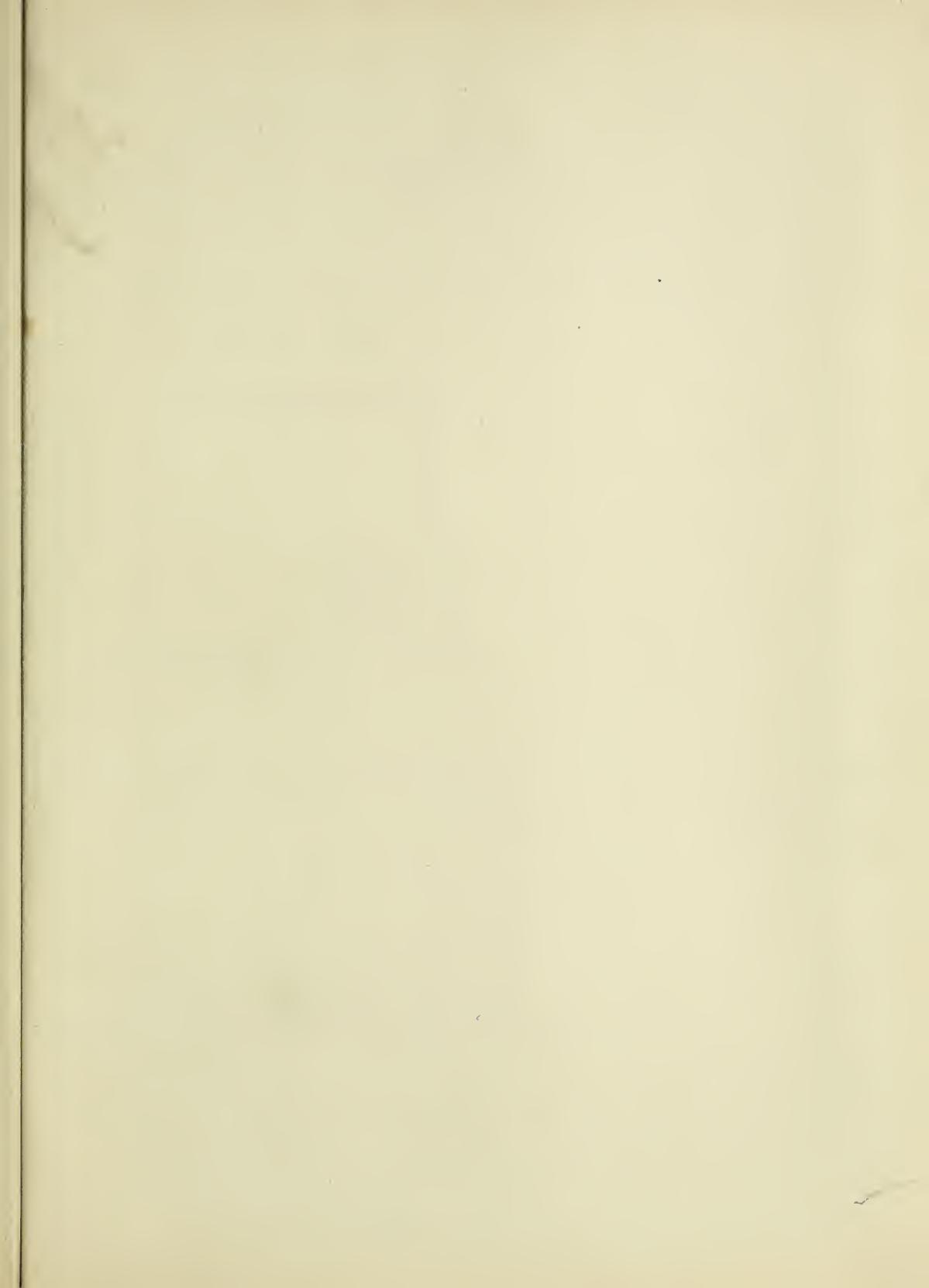
The precaution of watering the coal-dust in the vicinity of a shot before firing it, is probably the most effective that is known at the present time. This process, however, must be effectively done. If the surface of the dust be made simply damp, the danger would probably remain. The highly-heated products of an explosive would instantly vaporise the water in that damp surface, and set up distillatory action in the coal-dust. There was a degree of dampness in some of the Camerton dust ; but it was instantly vaporised and did not protect the coal from distillation, inasmuch as explosive gases were generated from this damp dust, and the explosions were propagated beyond, for a considerable distance. If the coal-dust be wet, the heat at disposal would doubtless be entirely absorbed in the vaporisation of the water present, and the coal-dust itself would be unaffected.

The significant remarks made by the last Royal Commission on Accidents in Mines, must be noticed. Referring to Mr. Galloway's opinion that coal-dust was the principal agent in coal-mine explosions, the Commission embodied the results of practical experience and scientific research up to that date, by observing that : " If coal-dust were the principal agent in coal-mine explosions, every blown-out shot occurring in a very dry and dusty mine, should actually be attended by a more or less disastrous explosion or conflagration ; and looking therefore to the enormous amount of powder expended in shot-firing in this and other countries, and to the not inconsiderable proportion which blown-out shots must constitute in many localities of the total number of shots fired,

disastrous coal-mine explosions should be of more than daily occurrence if his view were correct." * This conclusion now requires to be revised, for though the explosion at the Camerton Collieries is the only one which recorded observation has shown must have been due to the coal-dust, it yet leaves no room for doubt that the risk due to the presence of such dust in the workings of a mine, demands most serious attention. The nature of this risk will be seen, when it is remembered that a shot containing a moderate charge of gunpowder was fired in the ordinary conditions of the mine ; that after rupturing some of the strata, the products of the combustion of the powder then possessed a potentiality adequate to initiate a series of activities in the coal-dust, which produced gaseous explosions of considerable violence ; and that products were evolved in these gaseous explosions, which propagated them again and again with equal destruction through extensive distances in the roads of the mine in which coal-dust prevailed. The consequences which followed may be recalled in the loss of two lives, falls of varying magnitude over a mile of roads, the displacement of several thousands of tons of strata, the destruction of the separation doors and air-crossings of a large part of the Colliery, the suspension of the ventilation, the stoppage of important coal-producing districts, and a serious expenditure in restoring the mine to working order.

The existence of the danger arising from coal-dust in the workings of a mine, the comparatively limited quantity of unexpended heat in the products of an explosive, that suffices to originate activities which cause this danger to break out in insuppressible violence, and the potentiality of the awakened energies to propagate the explosions with irresistible strength, require to be realised. This realisation of the

* Final Report, 1886, pp. 47, 48.



danger will be most effectively gained by an appreciation of its practical conditions, a conception of the heat and energy necessary to its outbreak, and of the activities that follow; with an apprehension of the nature of the resulting phenomena in the path of its repeated development of explosive violence; and the Author will be well repaid for the labour he has expended in the production of this volume, if the observations and views which it embodies, are found to contribute to a thorough understanding of this danger in mining enterprise, which, though of recent recognition, has an importance which, all will admit, can hardly be exaggerated.

THE END.

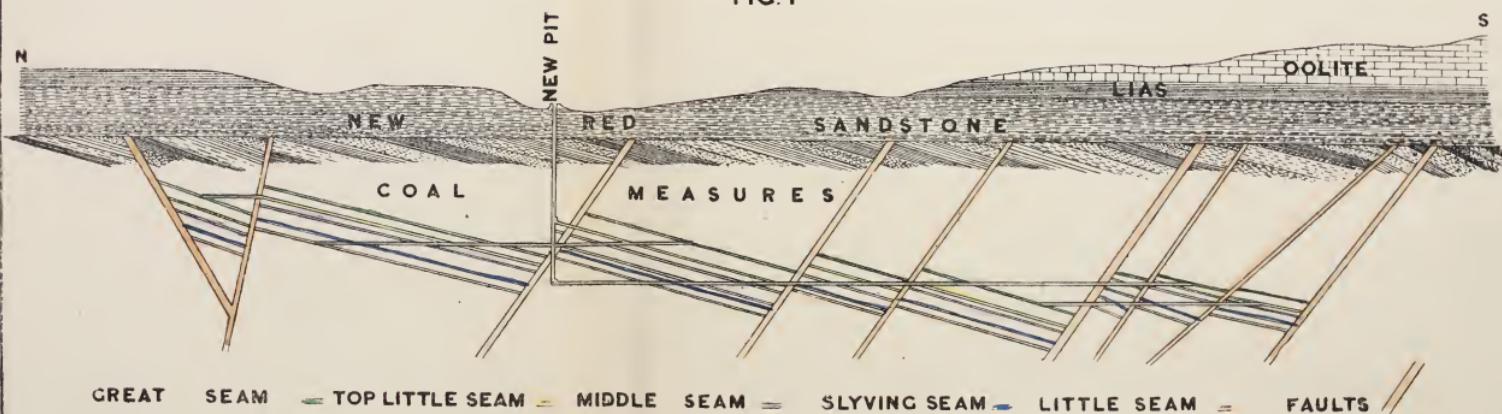
THE CAMERTON COLLIERIES

NEW PIT EXPLOSION

PLATE I

SECTION OF STRATA SHOWING CROSS MEASURE DRIFT

FIG. I



THE CAMERTON COLLIERIES
NEW PIT EXPLOSION

PLATE II

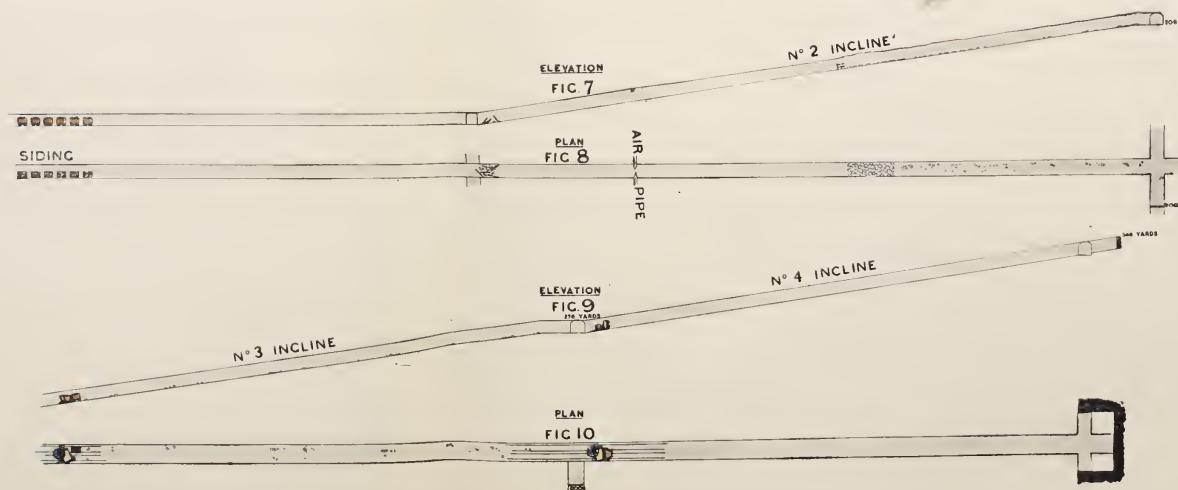
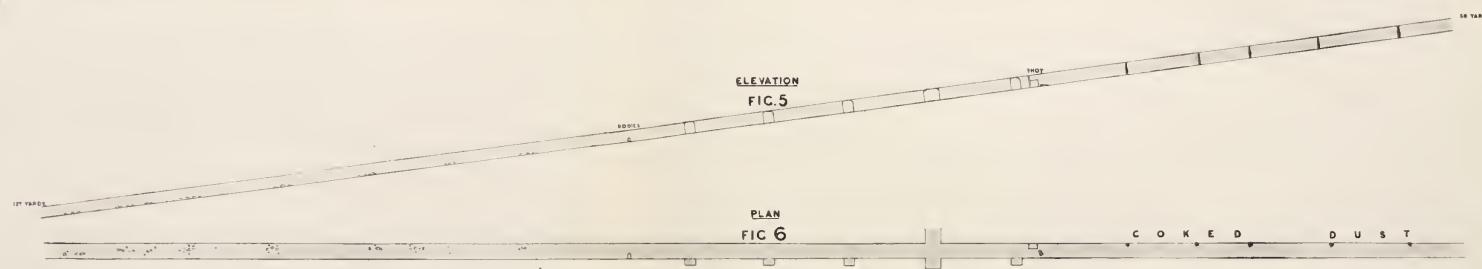
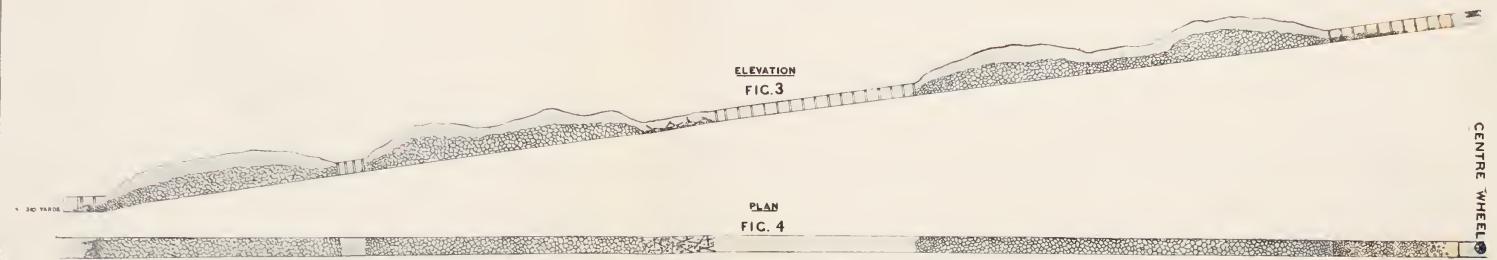
PLAN OF WORKINGS SHOWING THE COURSE TAKEN BY THE EXPLOSION



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PLATE III

LONGITUDINAL PLAN AND ELEVATION OF THE SOUTH EAST INCLINES

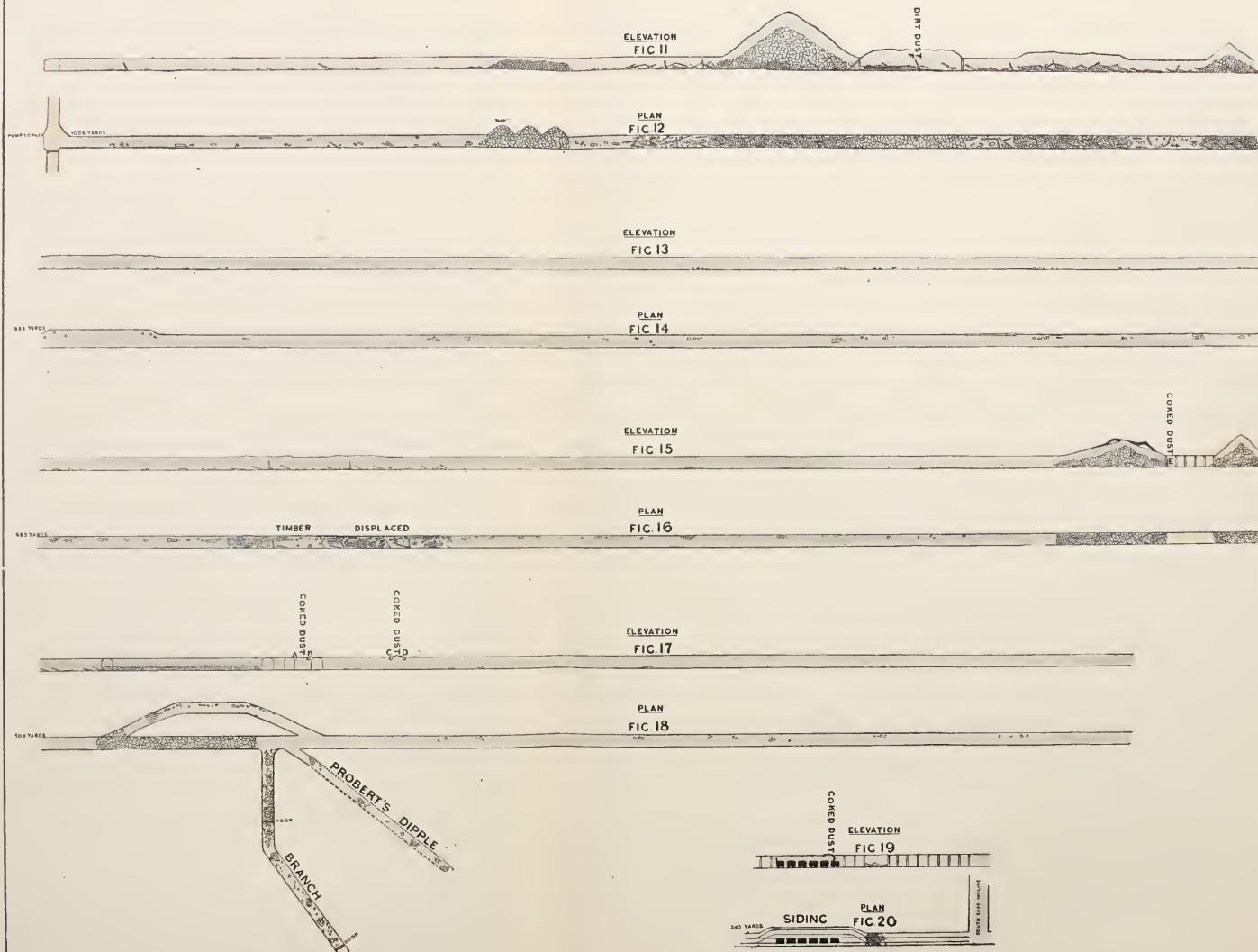


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PLATE IV

LONGITUDINAL PLAN AND ELEVATION OF HORSE ROAD FROM PUMP CORNER TO THE SOUTH EAST INCLINE



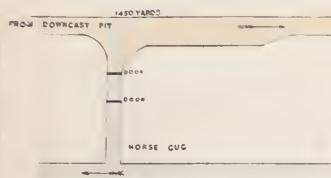
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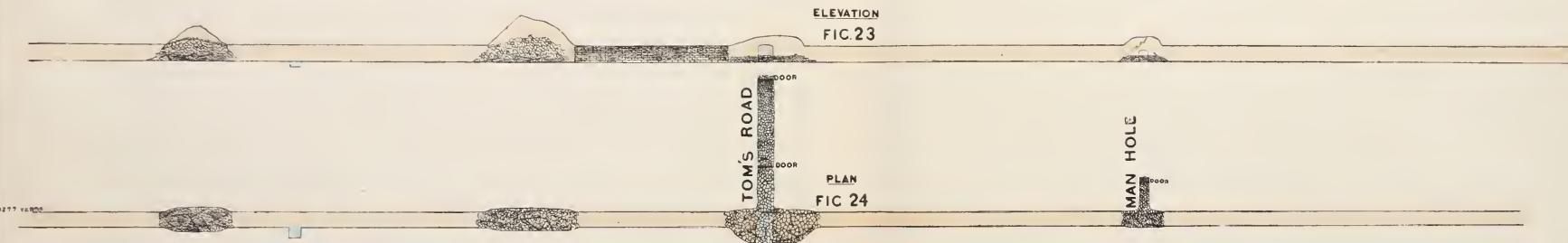
PLATE V

LONGITUDINAL PLAN AND ELEVATION OF MAIN INTAKE FROM HORSE CUC TO NEW BRANCH

ELEVATION FIG. 21



PLAN FIG. 22



ELEVATION
FIG 25

PLAN
FIG 26



THE CAMERTON COLLIERIES
NEW PIT EXPLOSION

PLATE VI

PLANS AND ELEVATIONS OF INCLINE WHERE THE EXPLOSION ORIGINATED

FIG. 27

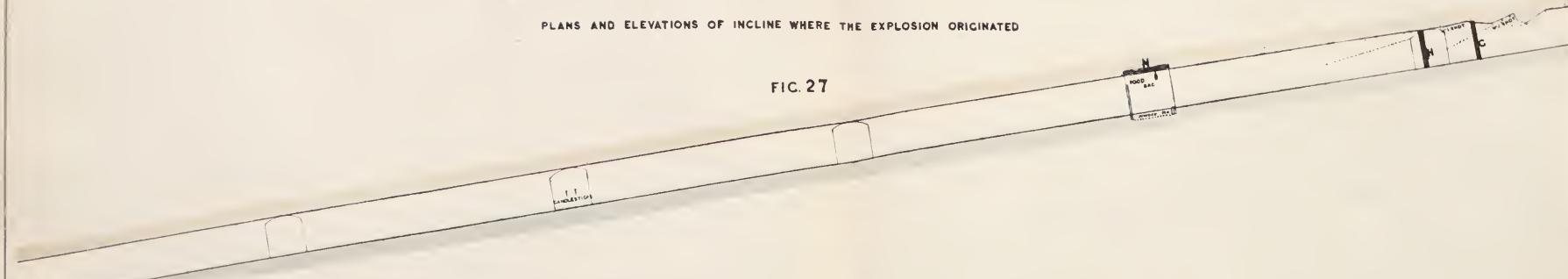
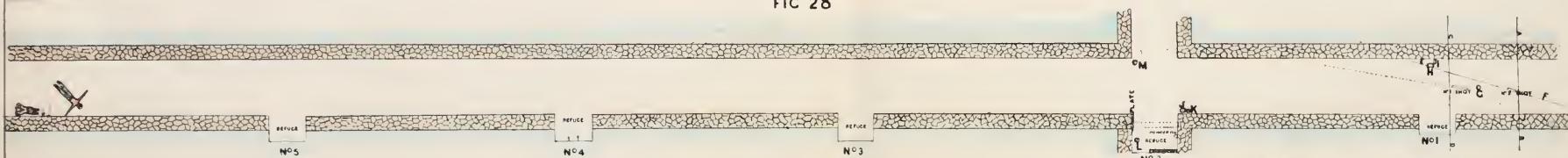


FIG. 28



FRONT ELEVATION THROUGH A-B

FIG. 29



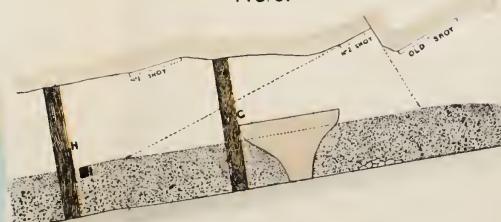
FRONT ELEVATION THROUGH C-D

FIG. 30



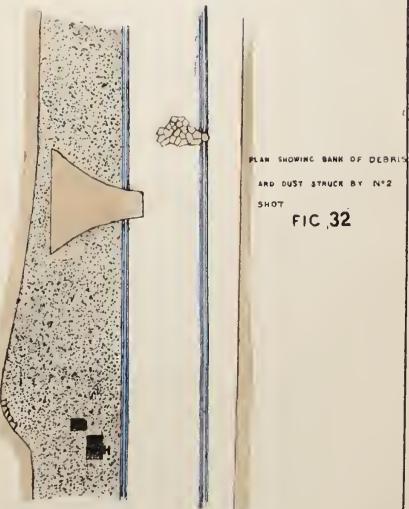
SIDE ELEVATION THROUGH E-F

FIG. 31



PLAN SHOWING BANK OF DEBRIS
AND DUST STRUCK BY N°2
SHOT

FIG. 32

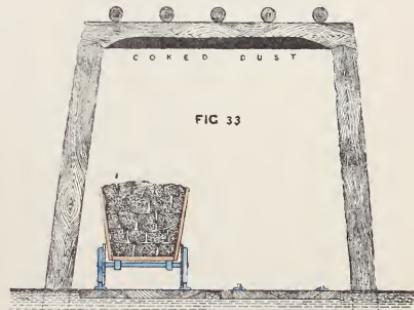


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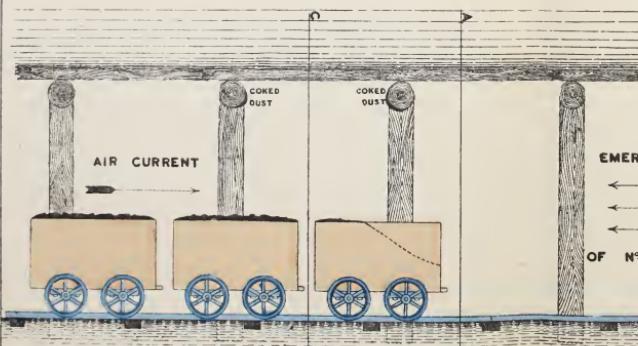
PLATE VII.

SECTIONAL AND FRONT ELEVATIONS OF SIDING AND SOUTH EAST INCLINE

SECTION THROUGH CD



SECTION THROUGH AB



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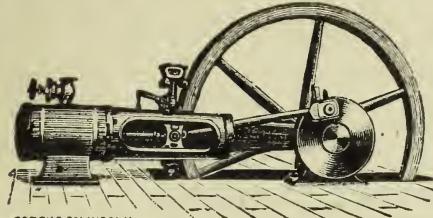
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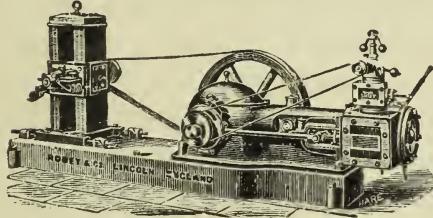
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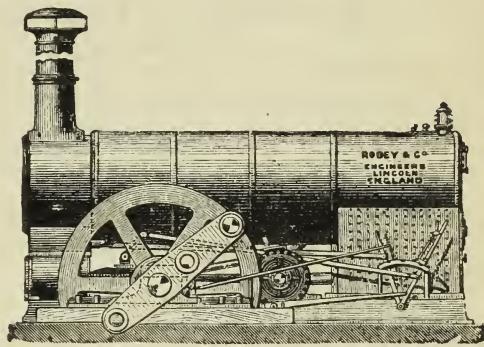


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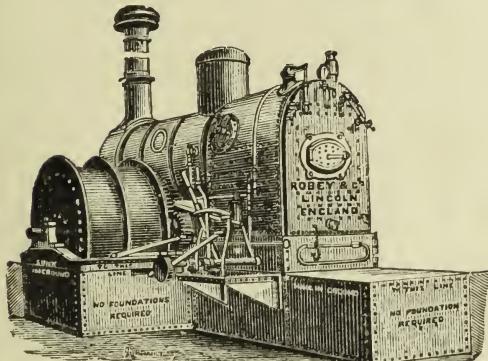
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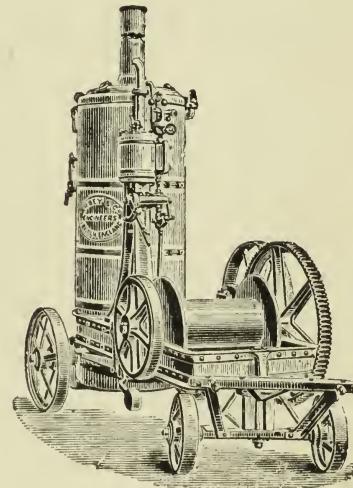
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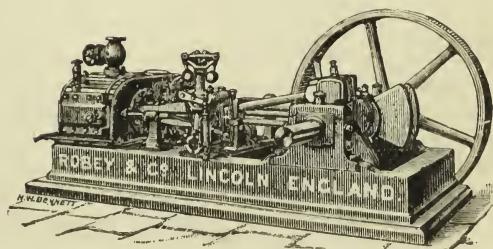
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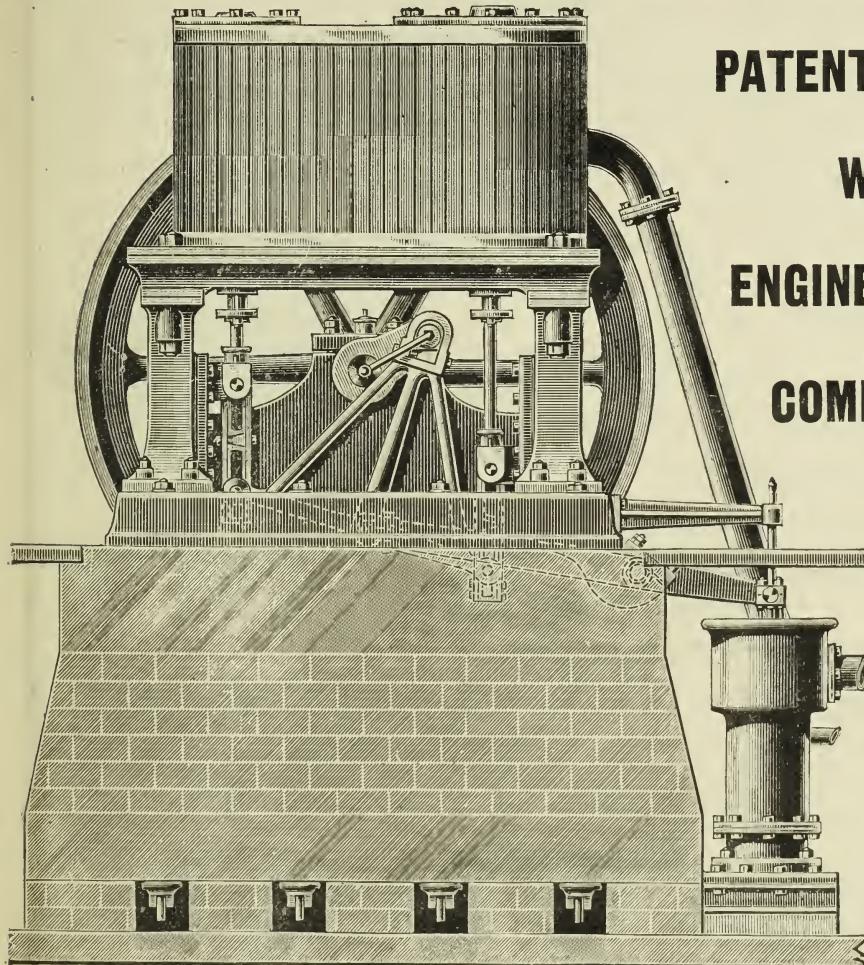
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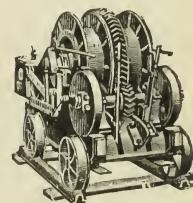
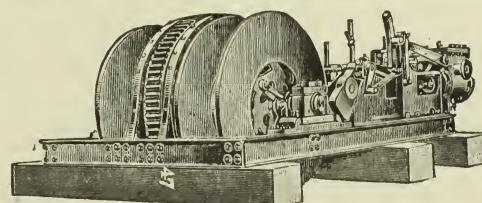
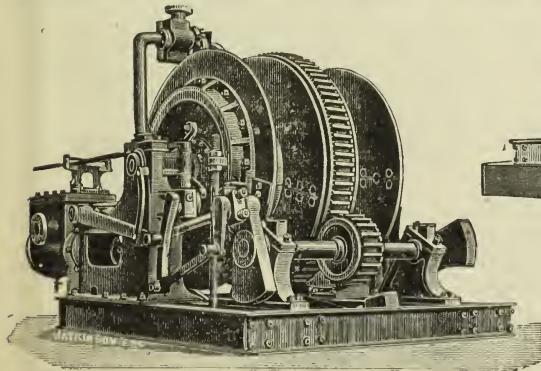
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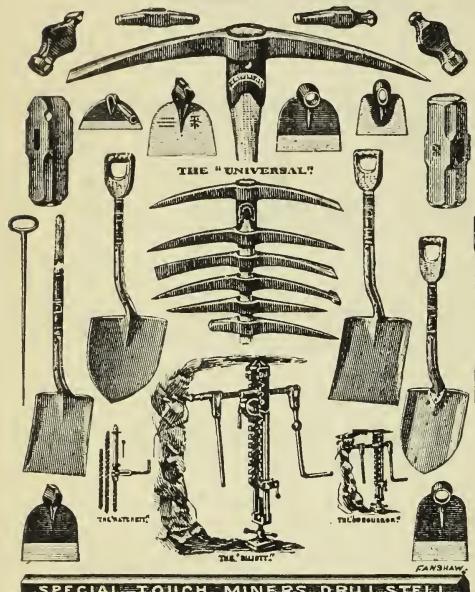
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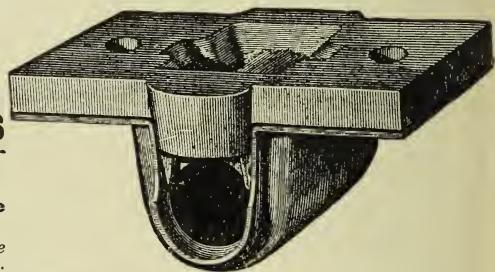
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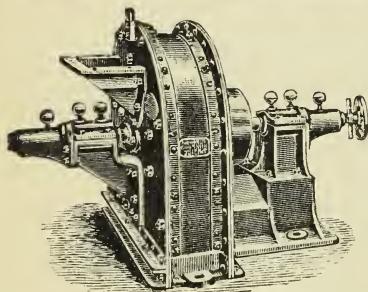
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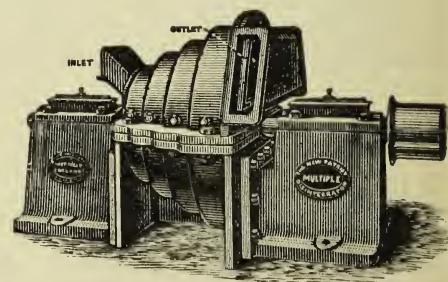
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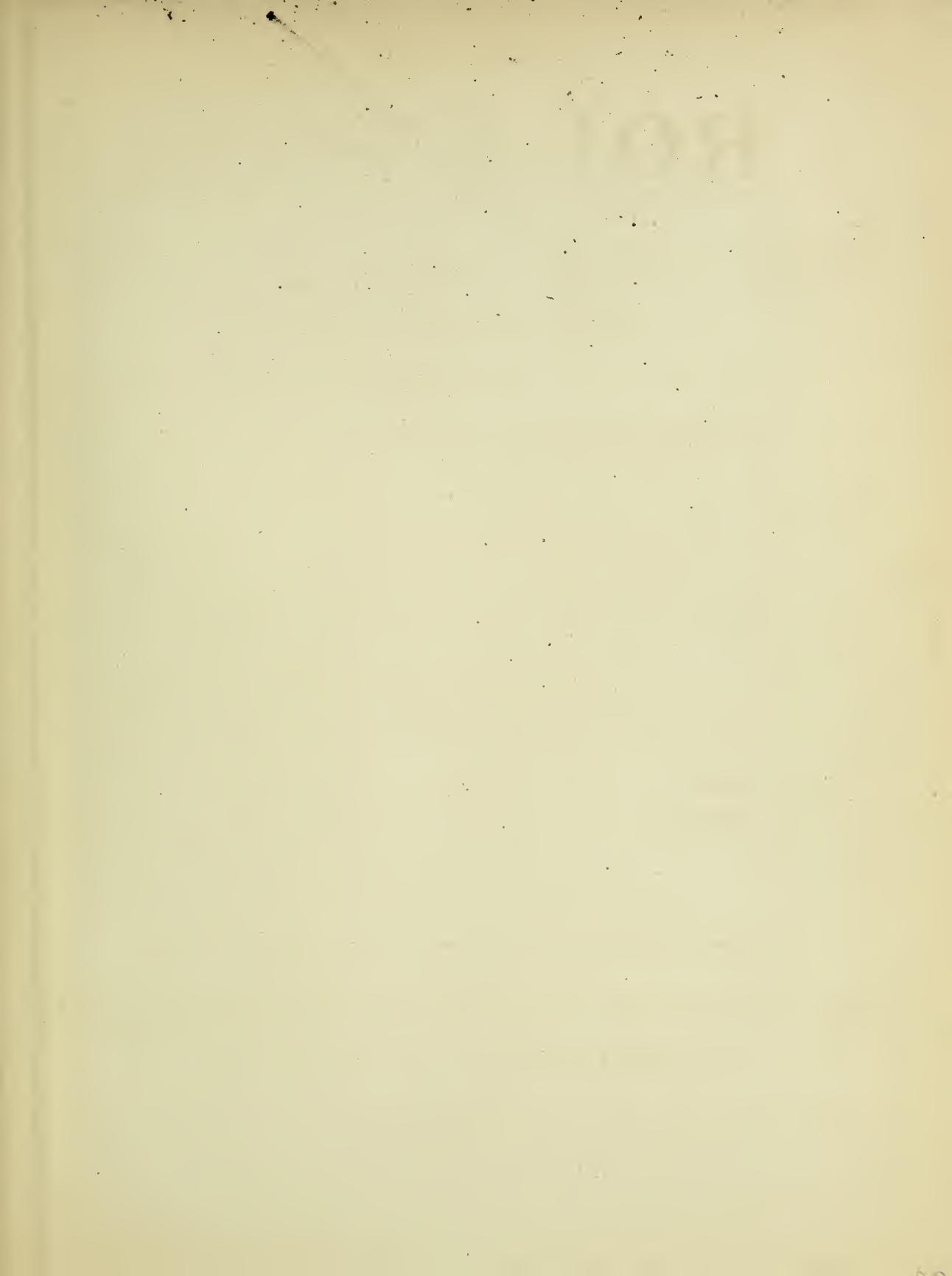
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